# RICOCHET

# Coherent Elastic Neutrino-Nucleus Scattering with Cryogenic Crystal Detectors

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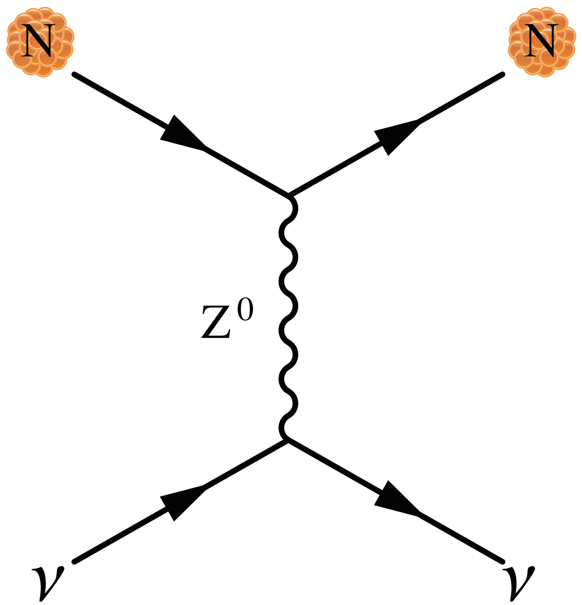
# Overview

- Coherent Elastic Neutrino-Nucleus Scattering
- Phonon detectors
- Ricochet at a Reactor
- Ricochet using electron capture source
- Conclusion

# Coherent Elastic ν-Nucleus Scattering

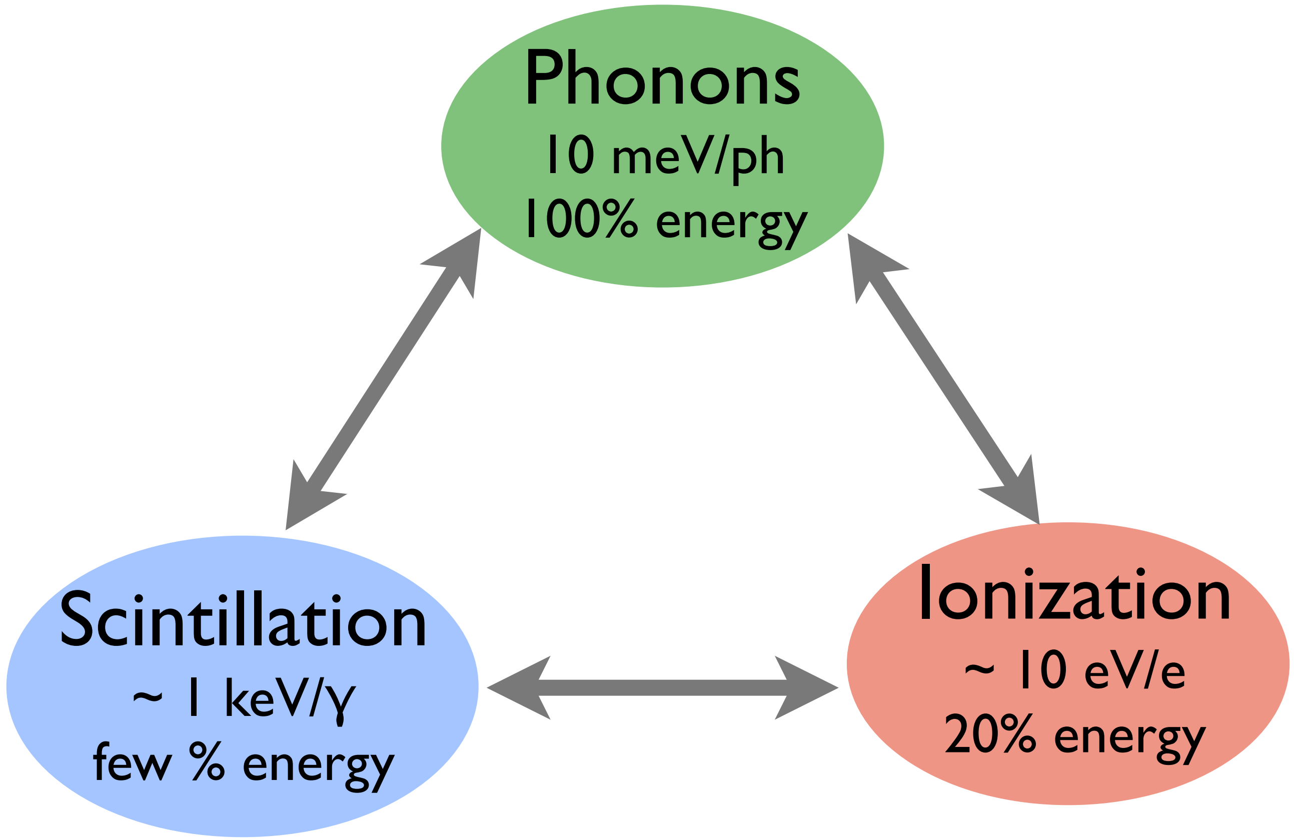
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

- σ: Cross Section
- T: Recoil Energy
- $E_\nu$: Neutrino Energy
- $G_F$: Fermi Constant
- $Q_W$: Weak Charge
- $M_A$: Atomic Mass
- F: Form Factor

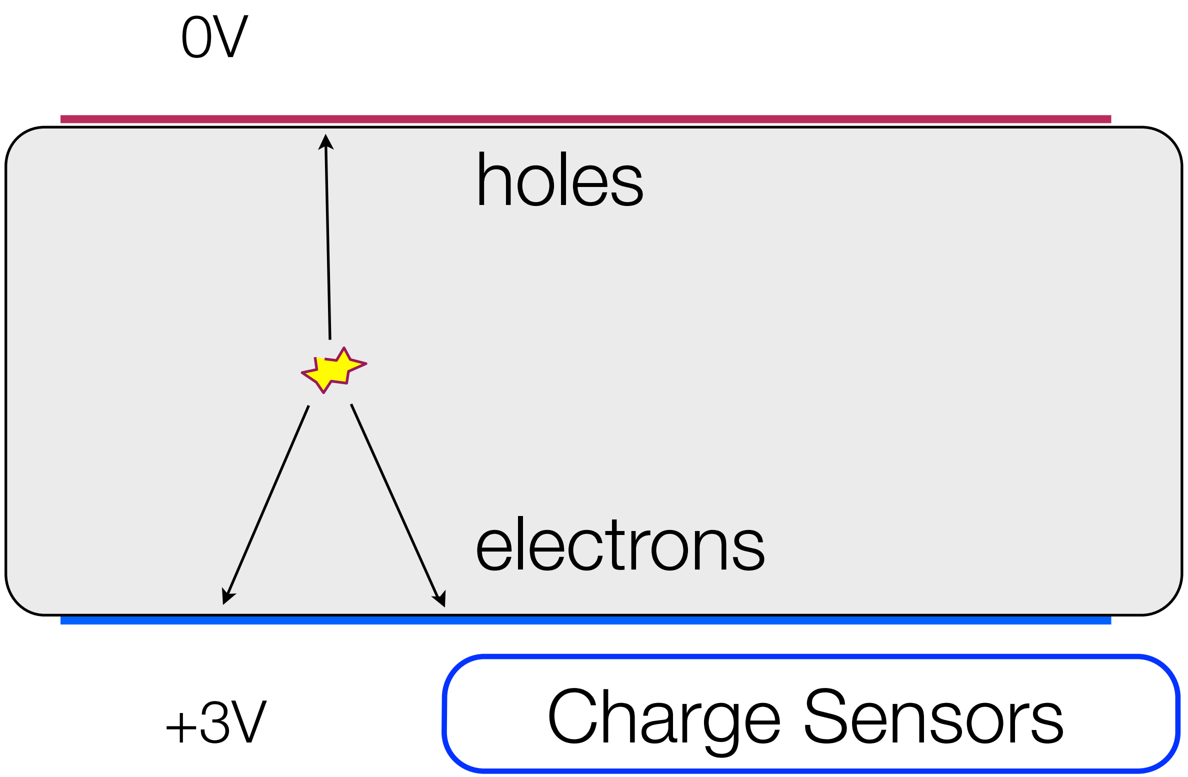



No flavor-specific terms!!!
Same rate for $\nu_e$, $\nu_\mu$, and $\nu_\tau$

# Low-energy recoils produce different products...



# CDMS II Detectors



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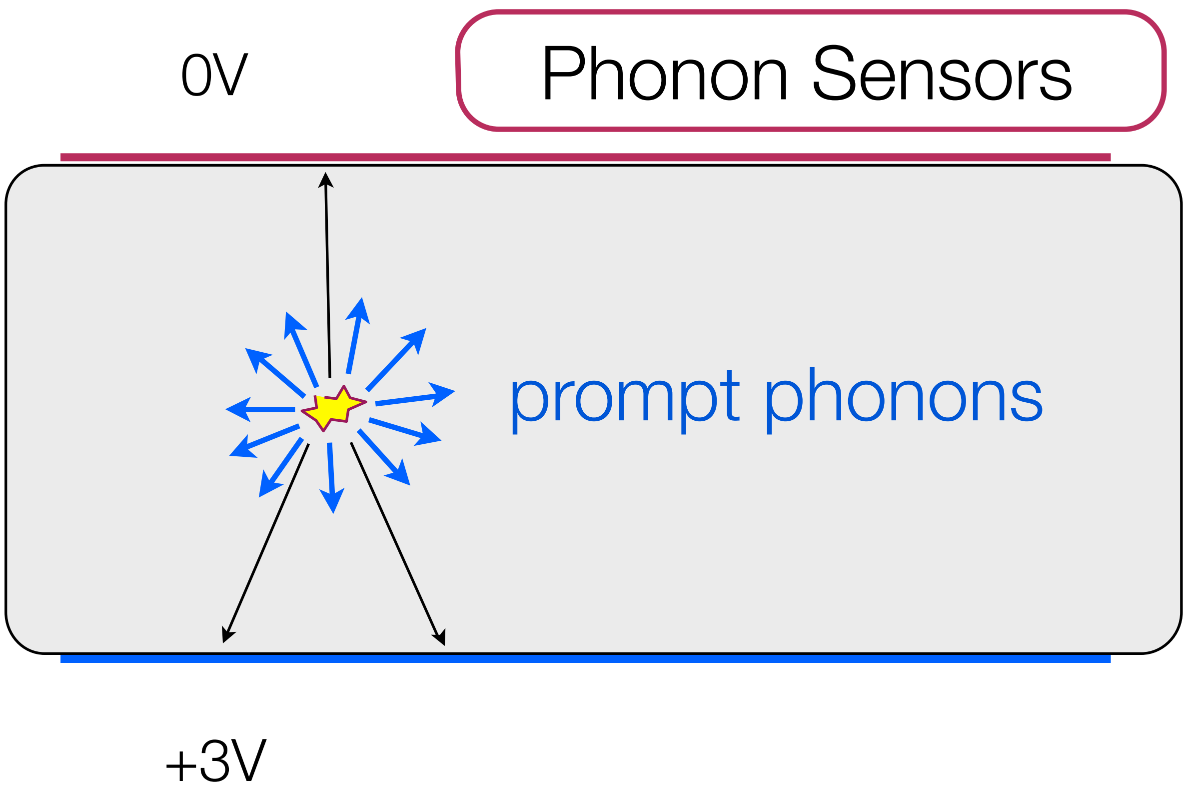
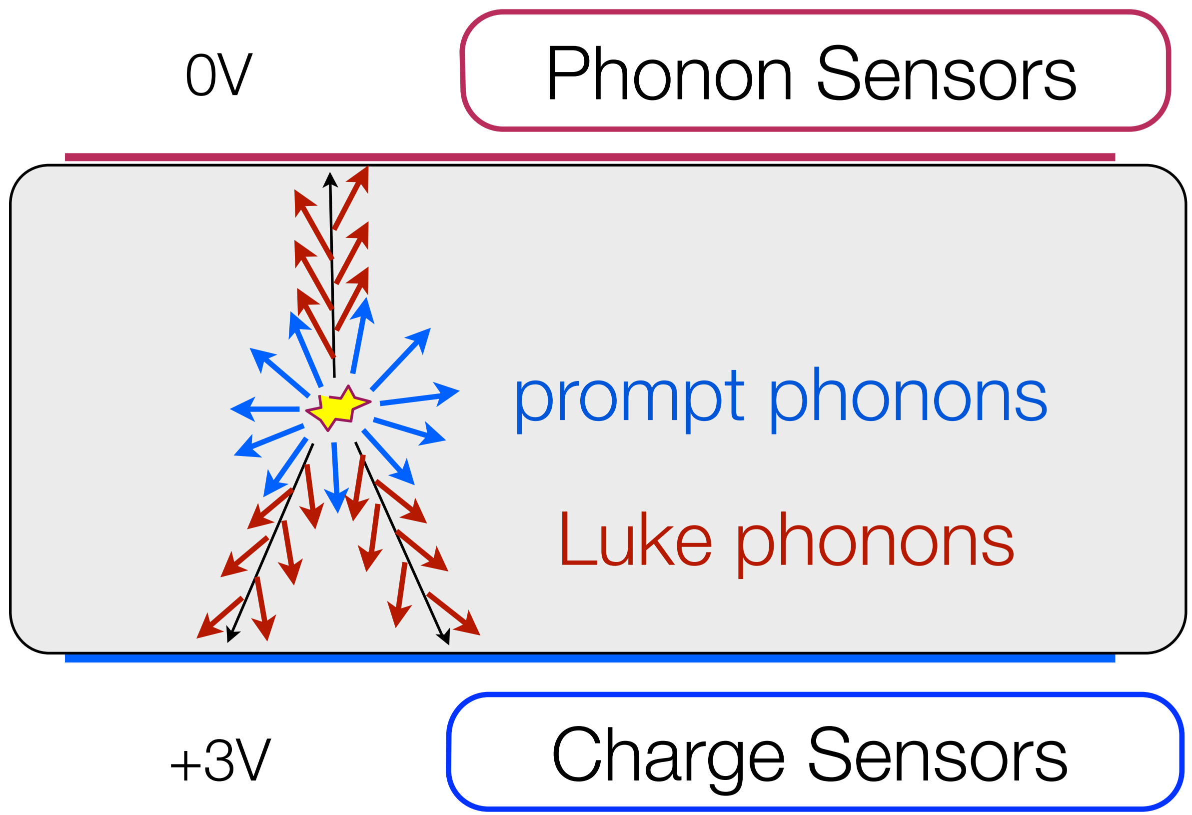


# CDMS II Detectors



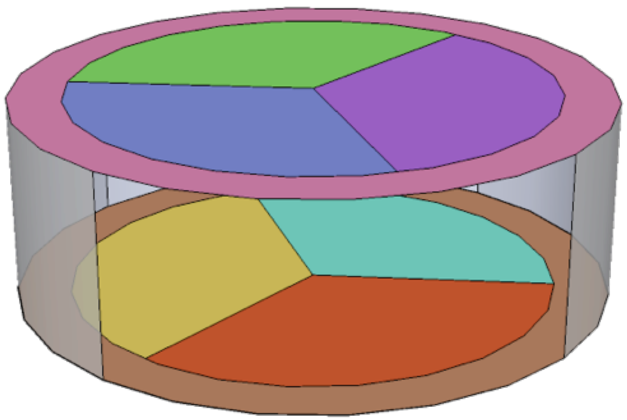

Luke Energy
$= \Delta V \, [e \, N_{eh}]$

$P_{tot} = E_{recoil} + E_{Luke}$

Luke phonons are used to read charge in special CDMSlite mode

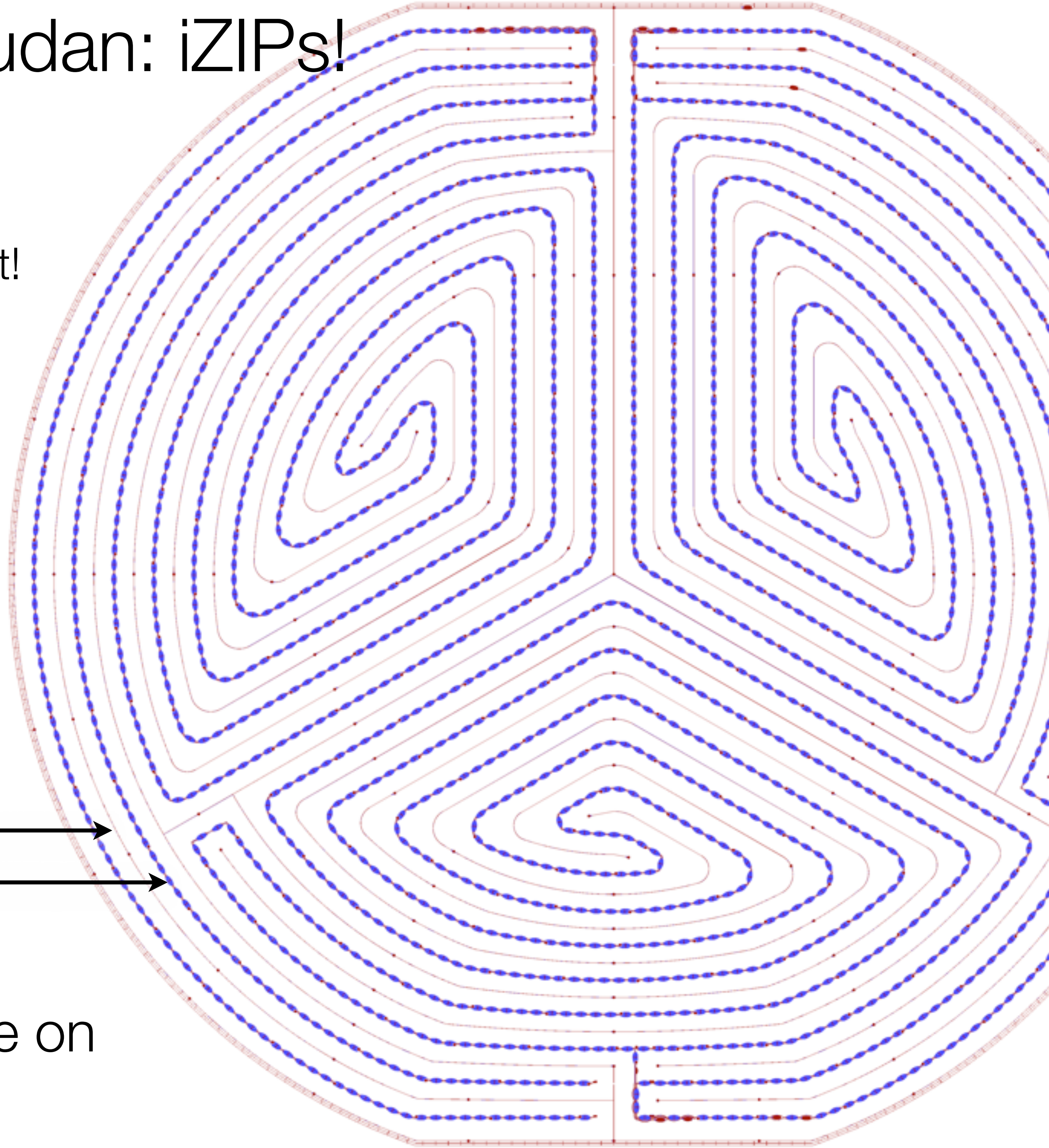
# SuperCDMS Soudan: iZIPs!

8 phonon channels +
4 charge sensors =
Lots of information per event!

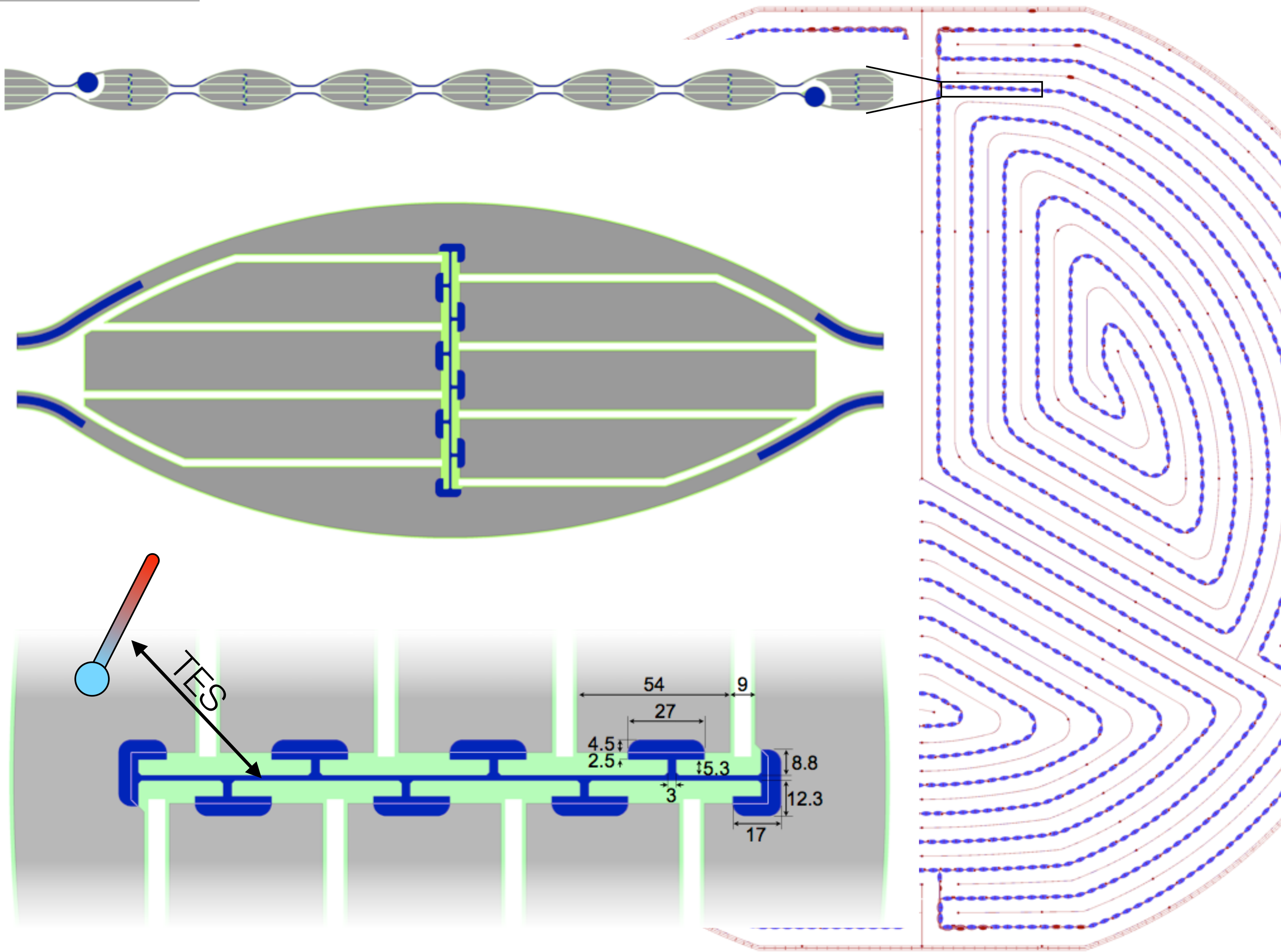


**charge sensor** (biased)

**phonon sensor** (grounded)

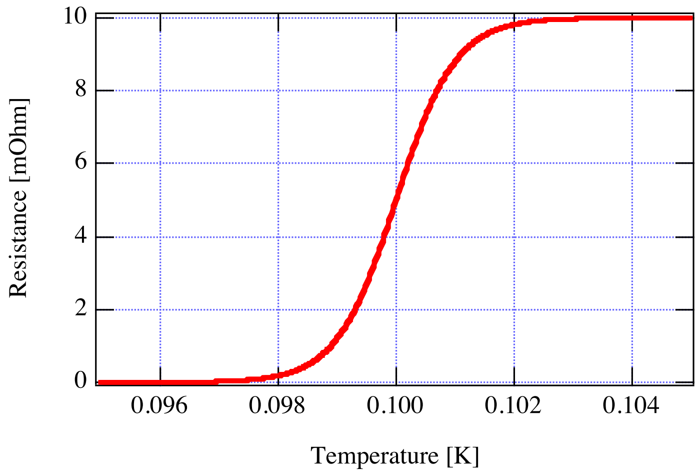


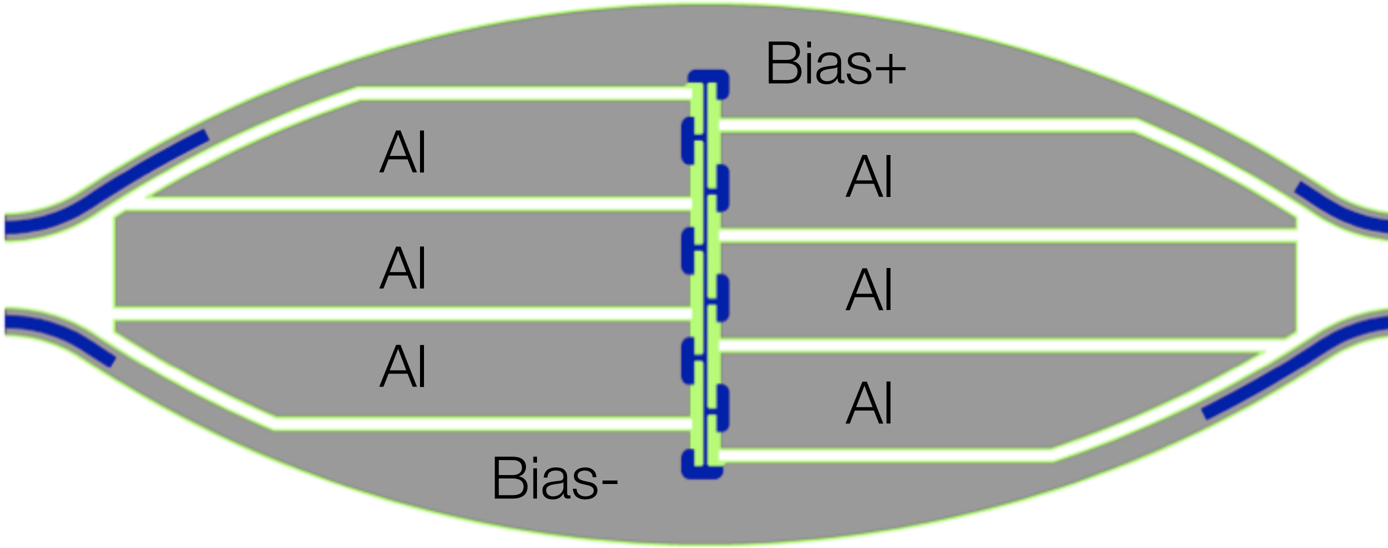
“interwoven”
phonon *and* charge on
each side!

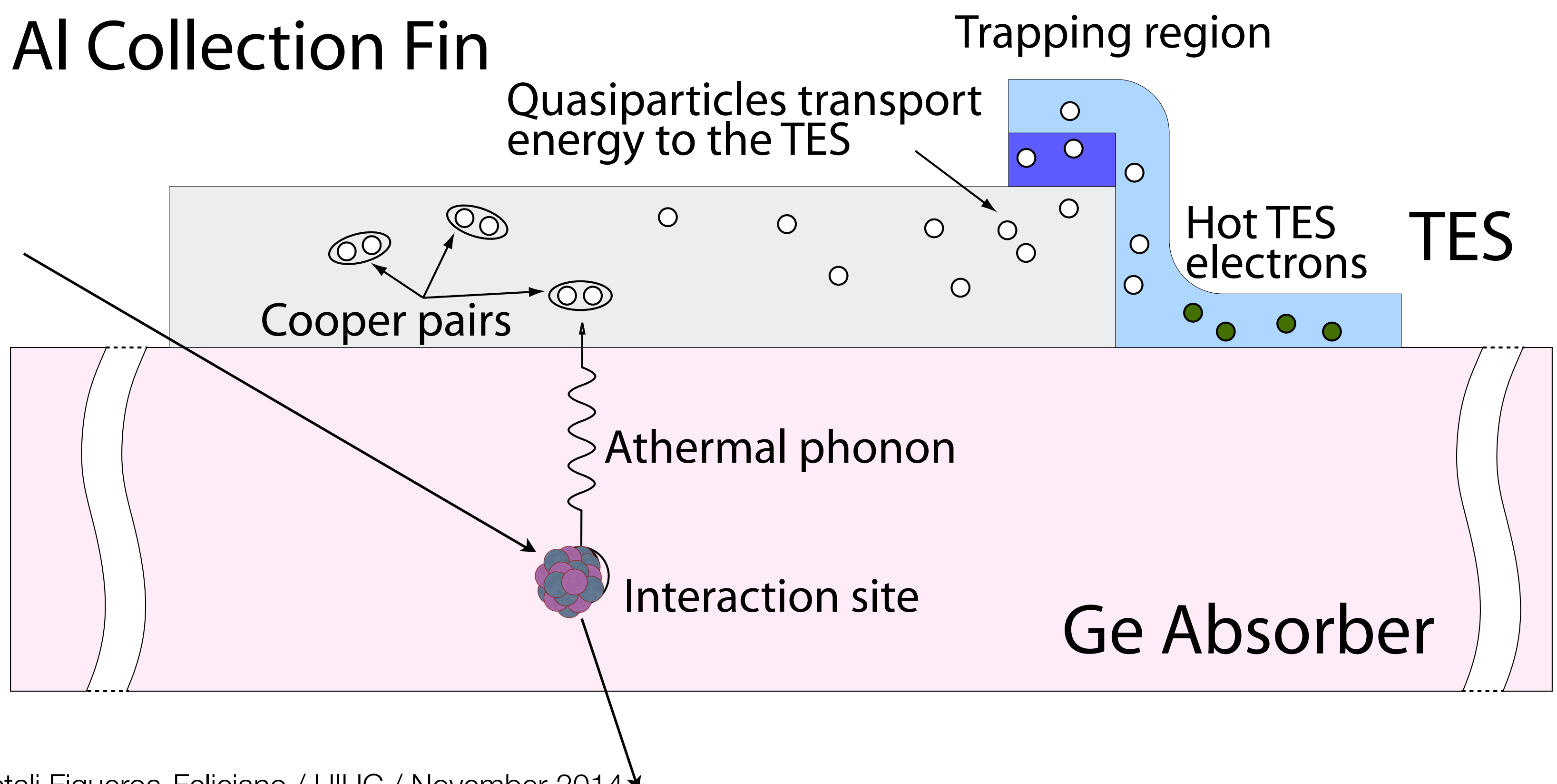


TES
54
9
27
4.5
2.5
5.3
3
8.8
12.3
17

# Getting Energy to the Sensors

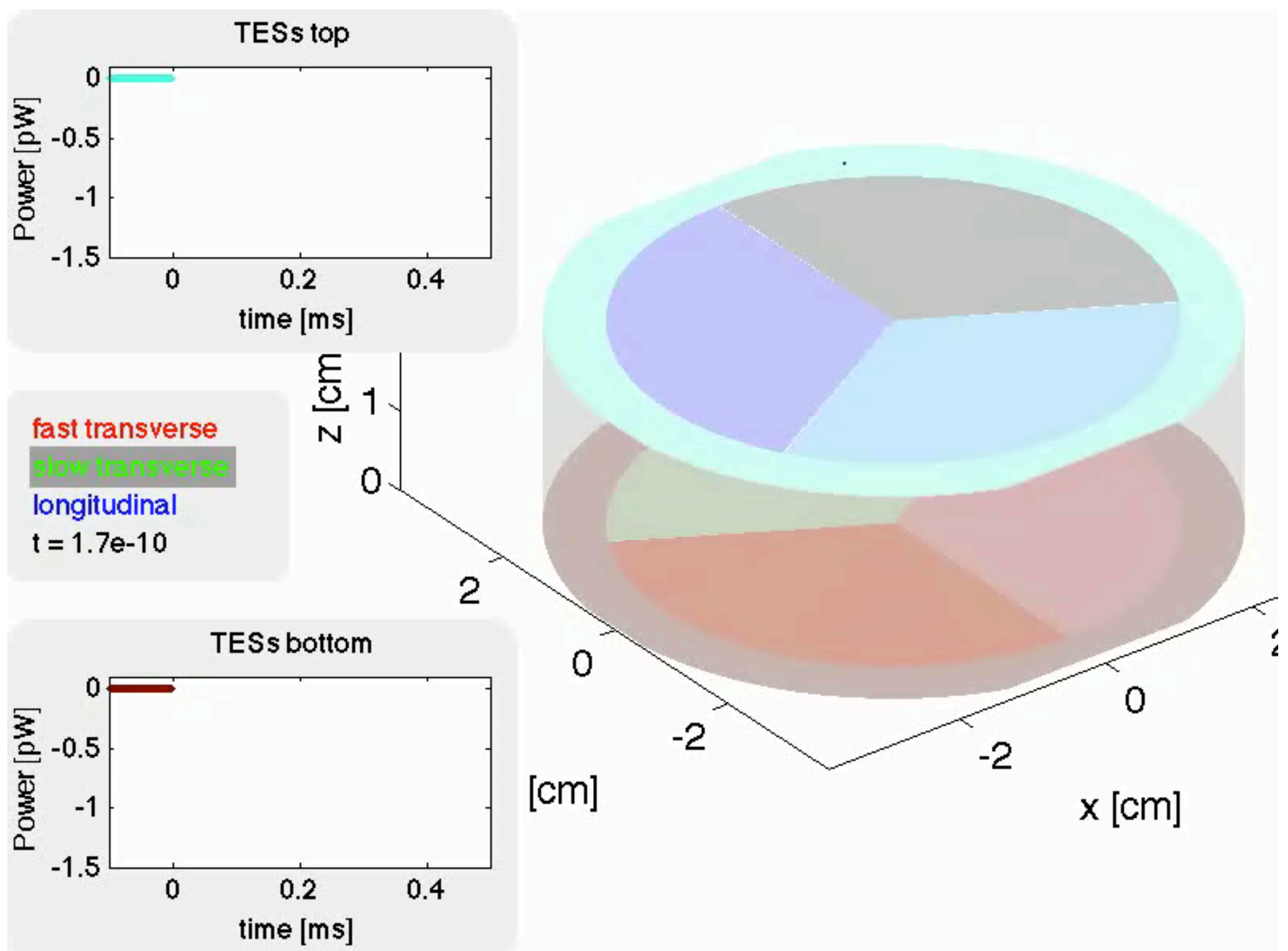


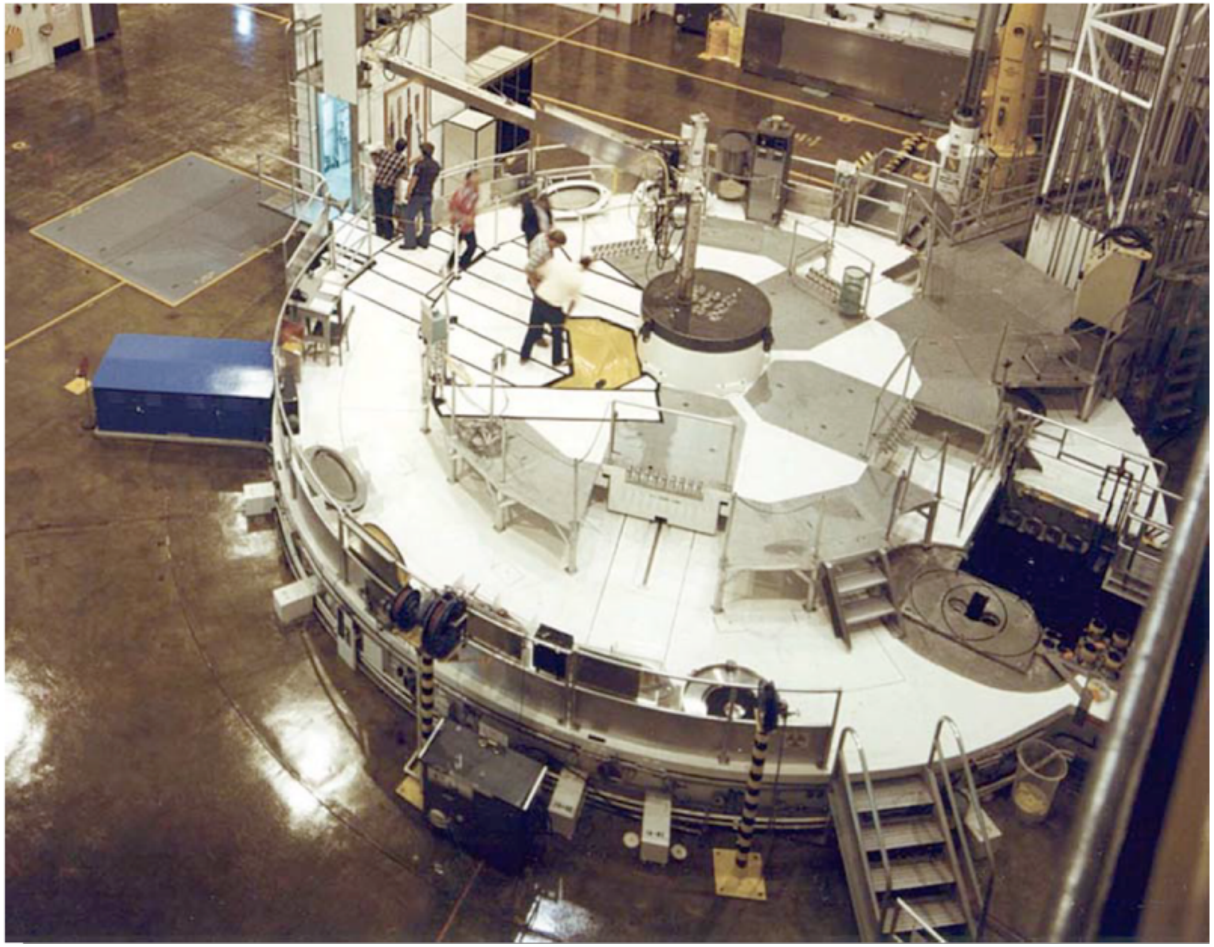
# CDMS Detector Monte Carlo (DMC)

- We developed a Matlab-based Detector Monte Carlo (DMC) which incorporates the physics of phonon transport, electron and hole transport, and TES energy collection and response.
- The output can be piped to our standard processing software and compared side-to-side with real data.
- The SLAC group has transported the DMC to GEANT4 and incorporated it into our SuperCDMS GEANT simulation



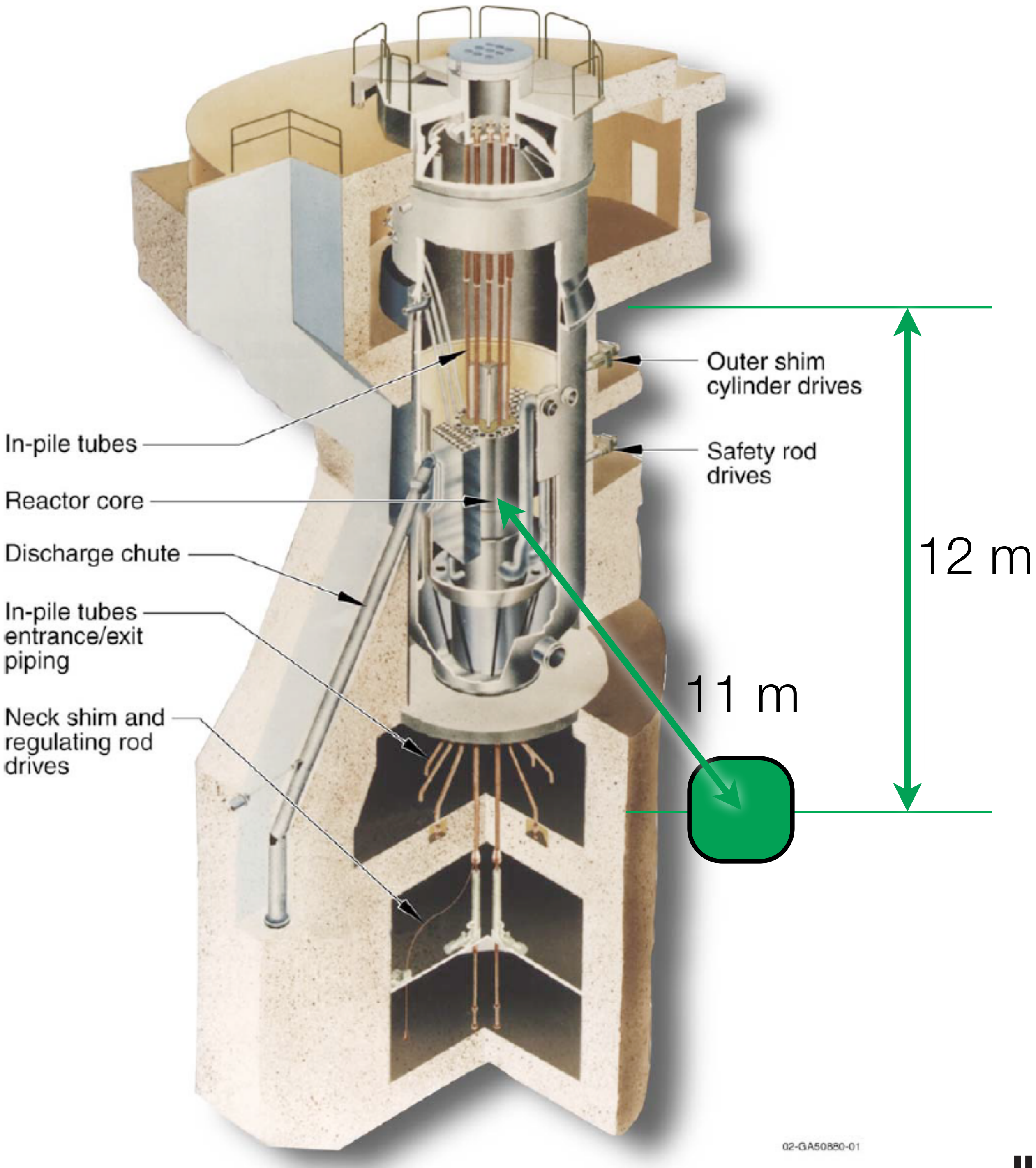
# Advanced Test Reactor (ATR), Idaho Nat. Lab.

- 110 MW Thermal Reactor
- $2 \times 10^{19}$ ν/s
- $1.2 \times 10^{12}$ ν/cm$^2$/s @ 11 meters from core
- 6-8 weeks on, 1-2 weeks off operating cycle

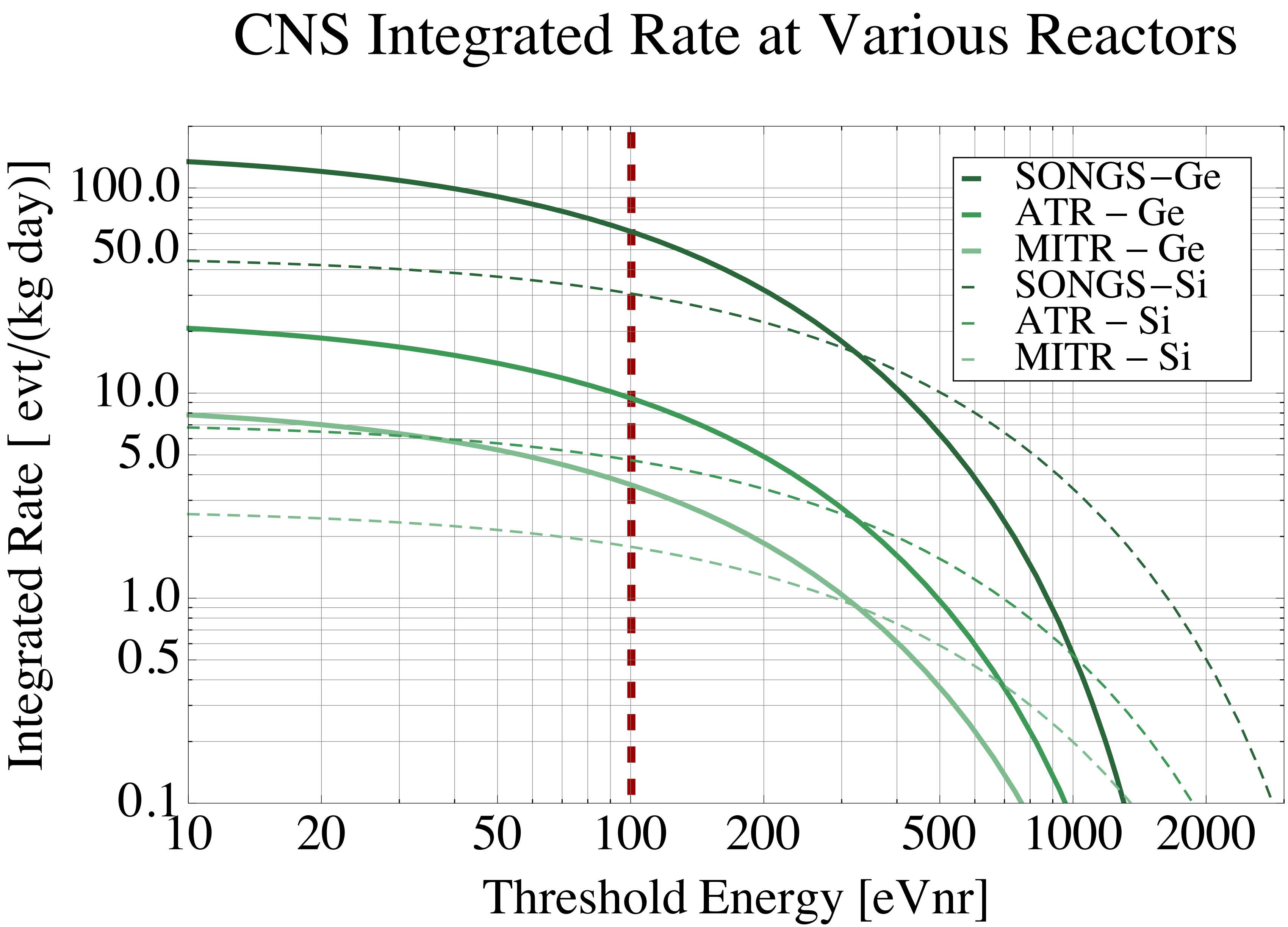


# ATR experimental site

- Potential Sites:
  - In first basement (outer shim corridor), 7 m from the core
  - In second basement, 11 m from the core

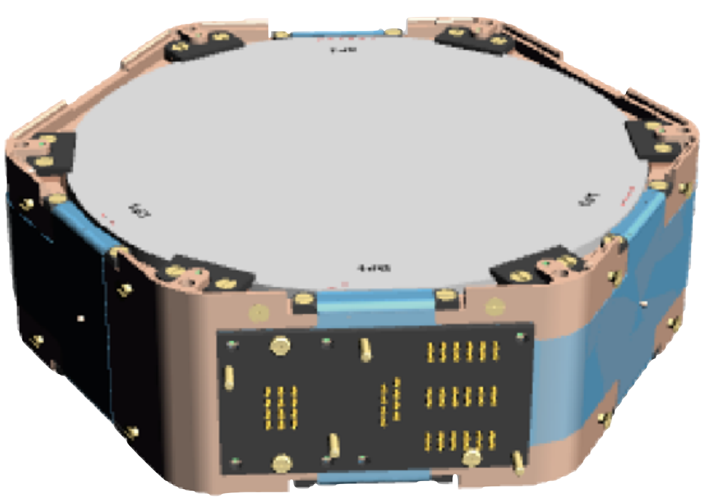


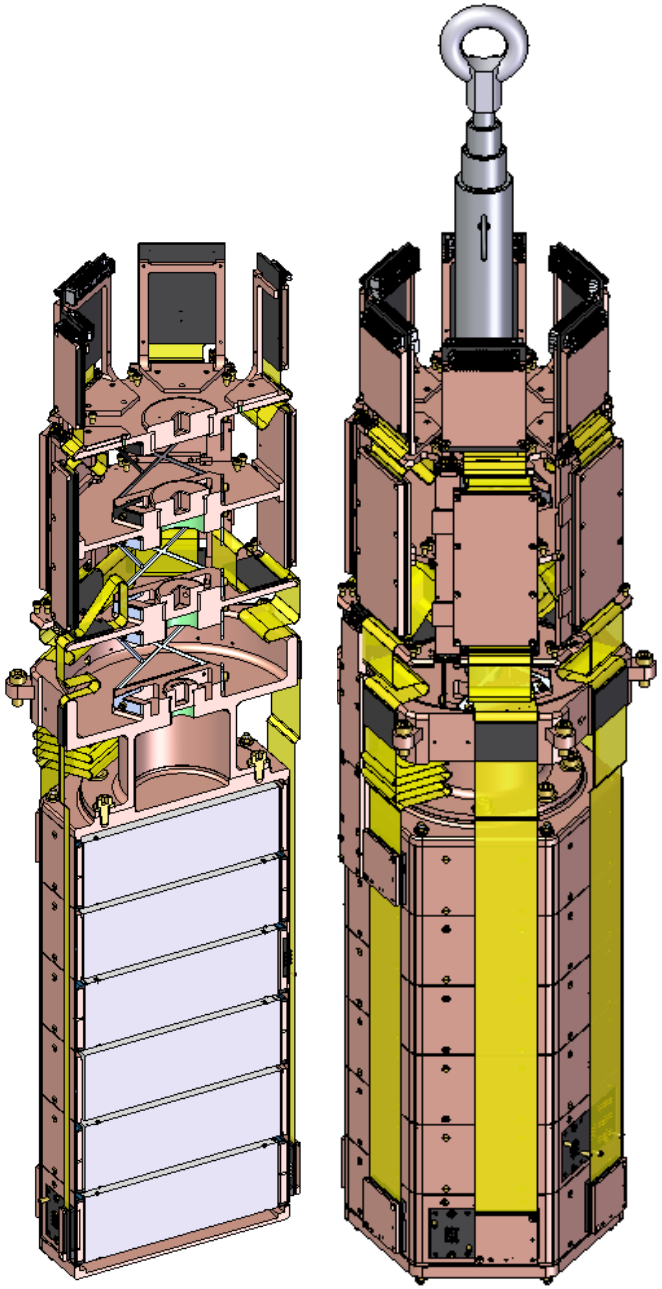
# CEvNS Signal



# Ricochet Phase 1: SuperCDMS Tower at a Reactor

- Leverage R&D and Engineering being done by the SuperCDMS G2 Experiment.
- 1 Tower holds 6 detectors, 100 eVnr Threshold
- 4 Si Detectors = 2.4kg Si = 11 CEvNS events per day
- 2 Ge Detectors = 2.8kg Ge = 26 CEvNS events per day
- **>7000/1000/400** events per month at the SONGS, ATR, and MIT reactors
- **>20** events per month at the SNS (for comparison)





# Backgrounds

We have a good handle on the signal, but what about the backgrounds?

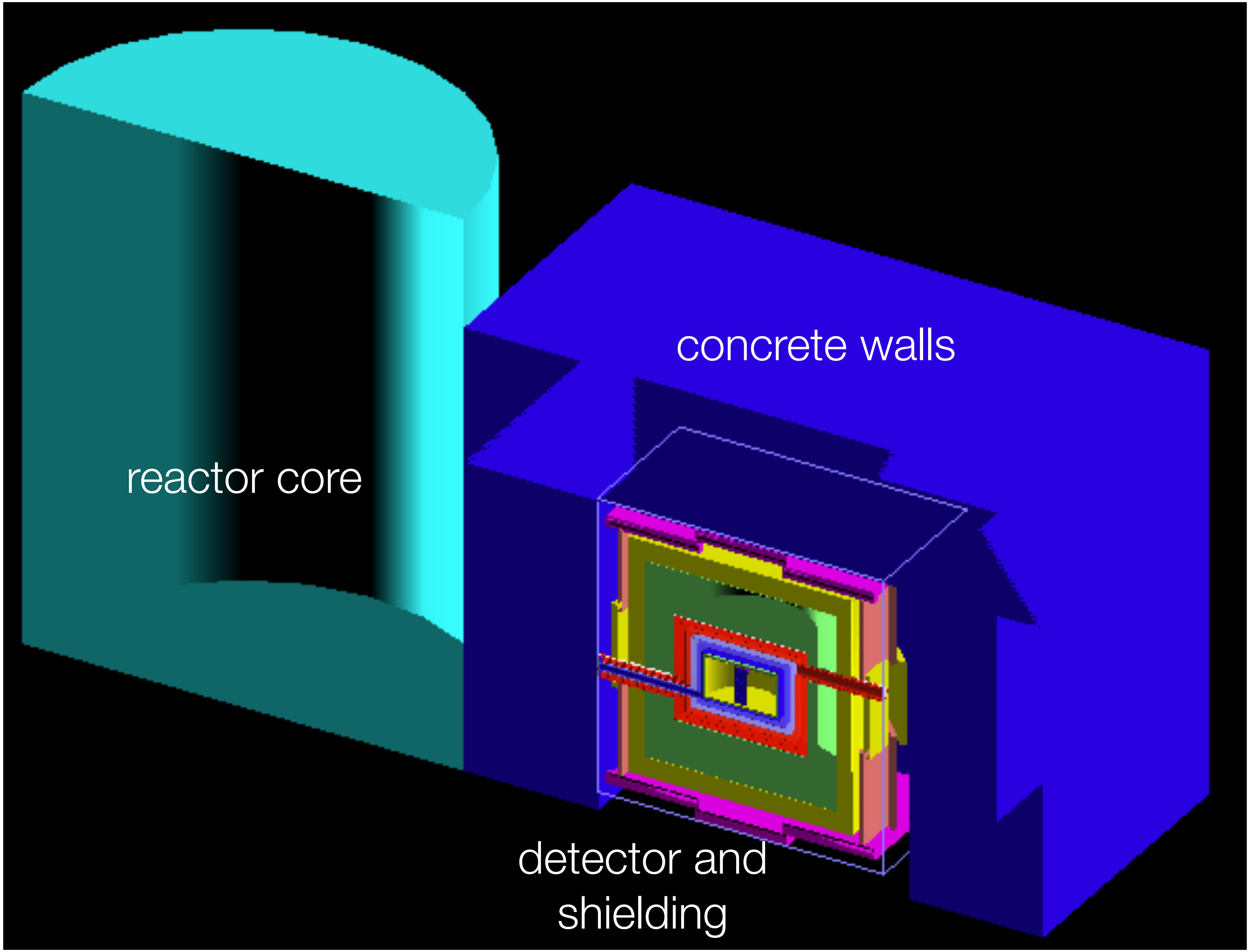
We have been working on this at MIT, but today we are only showing a work in progress..

We assume no electron/nuclear recoil discrimination, thus our backgrounds are composed of $\gamma$, $\beta$, n, and $\alpha$ coming from:

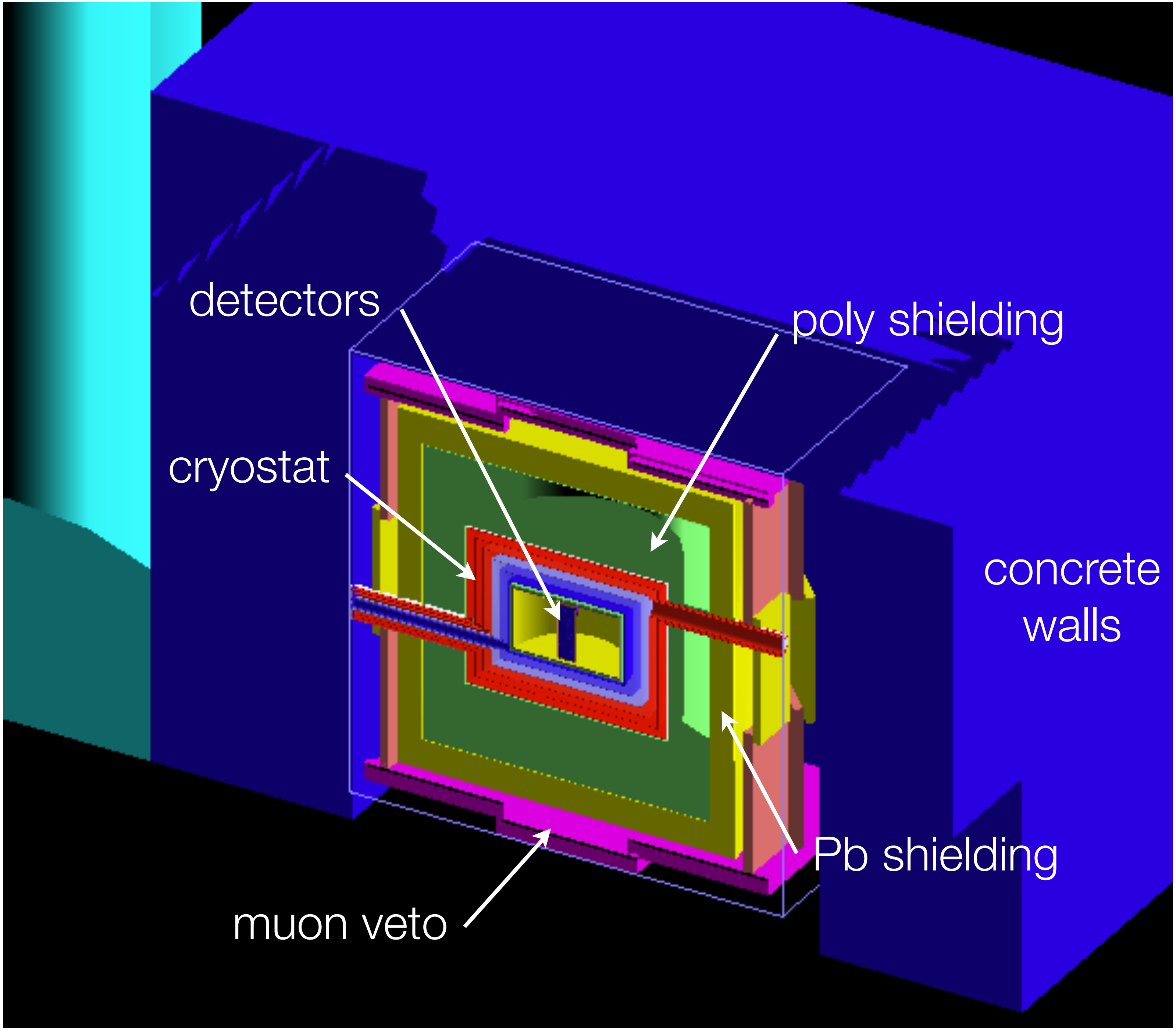
- Cosmogenic backgrounds
- Radiogenic backgrounds
- "Reactogenic" backgrounds

We are measuring the gamma and neutron backgrounds directly...

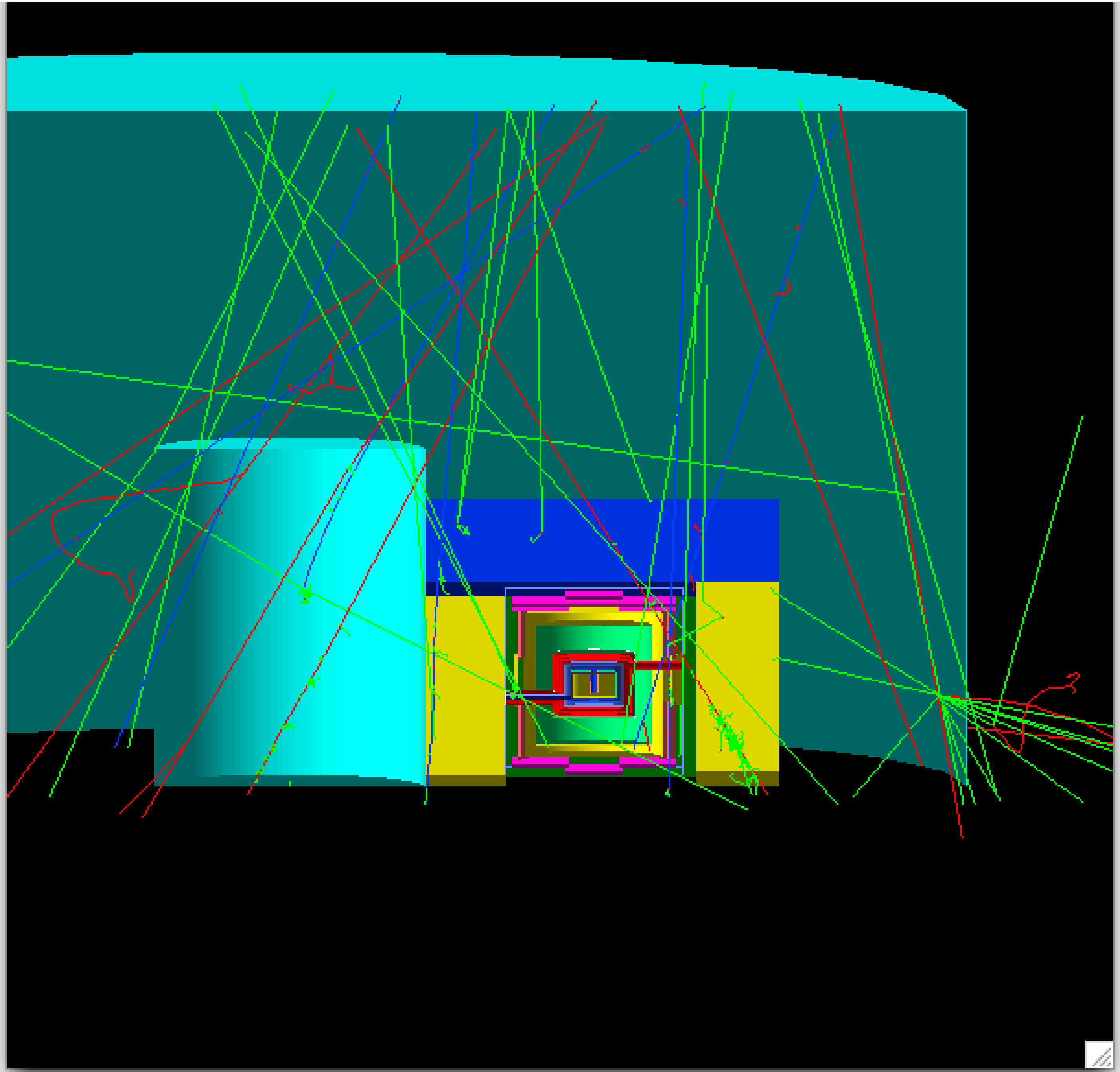
# Ricochet Monte Carlo in GEANT4



# Ricochet Monte Carlo in GEANT4



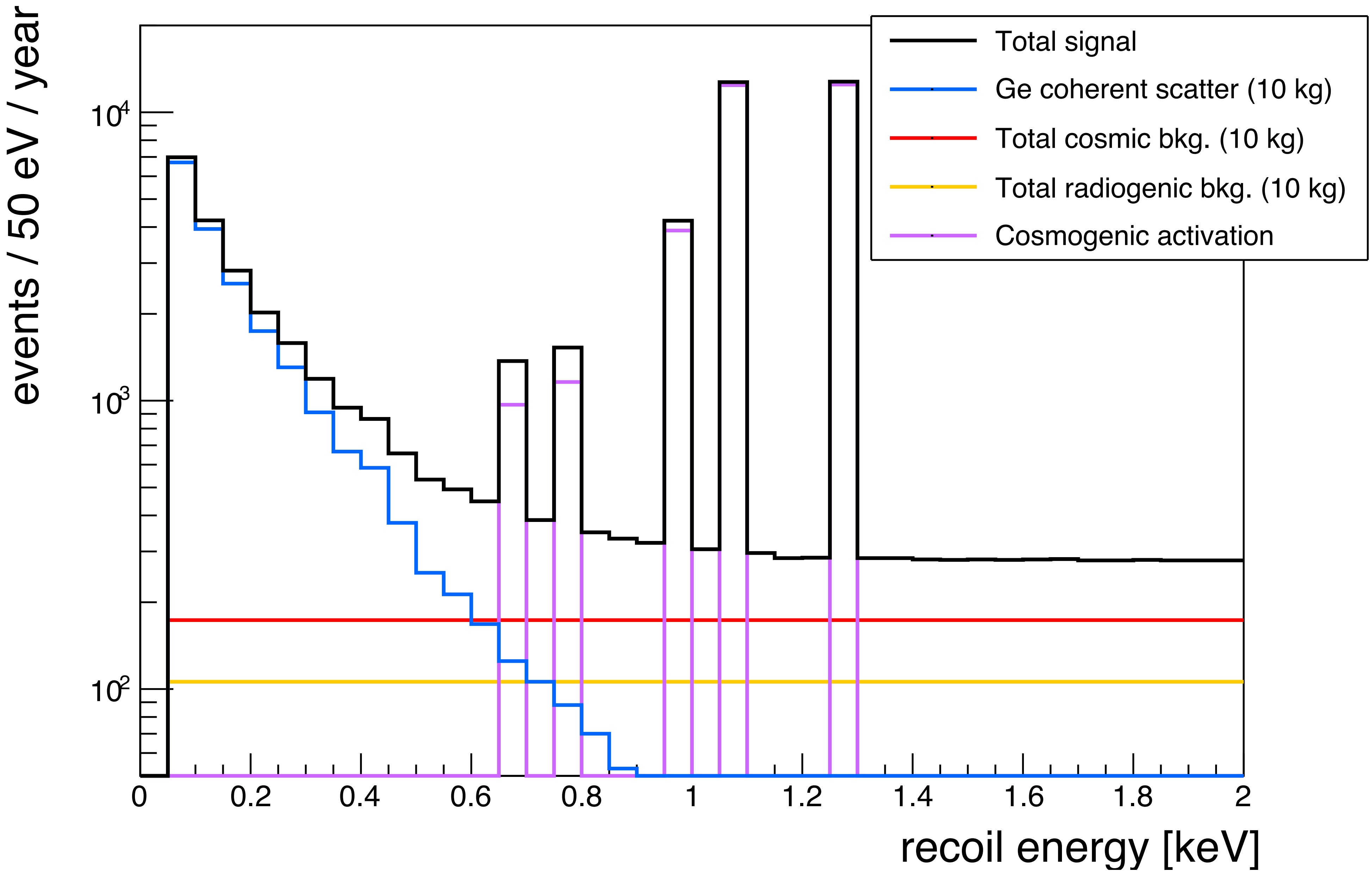
# Cosmogenic Backgrounds



# Putting together what we have so far...

- Created simulated signal and background spectra for MITR and ATR sites.
- What is in:
  - CEvNS signal
  - Cosmogenics: full CRY simulation with latitude, altitude, and seasonal corrections
  - U, Th, and K in Poly and Pb
  - L-shell electron capture lines from cosmogenic activation of Ge due to the isotopes: 68Ge, 60Co, 65Zn, 58Co, 57Co, 56Co, 54Mn, 55Fe
- What is not in:
  - Residual U, Th contamination of copper housing
  - Cosmogenic or “Reactogenic” activation in shields and housing
  - Radon daughters (surf. evnts)
  - Neutron Background from reactor
  - Unknowns (atomic transitions, etc..)
- This is a work in progress!!!

# MIT Simulated Spectrum



# Conclusions

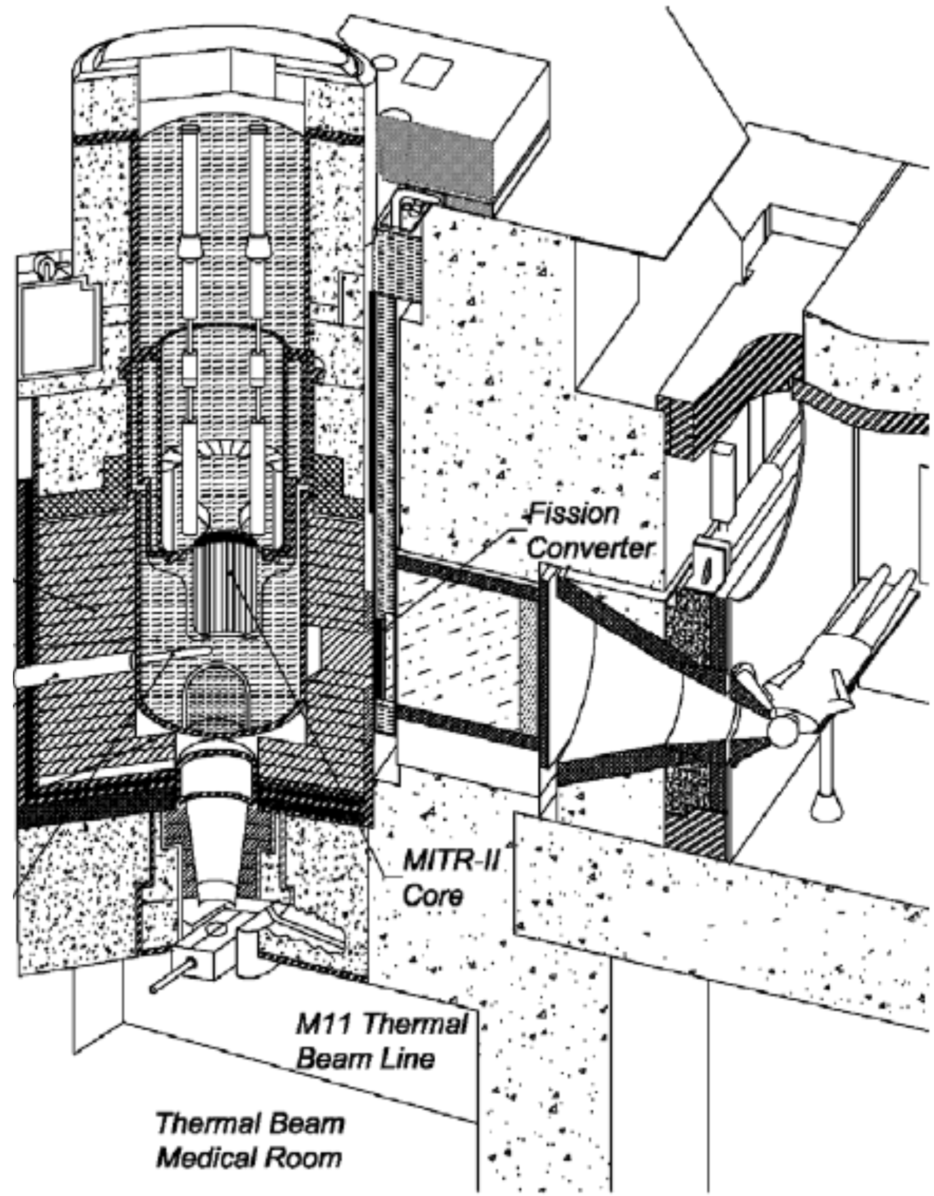
RICOCHET

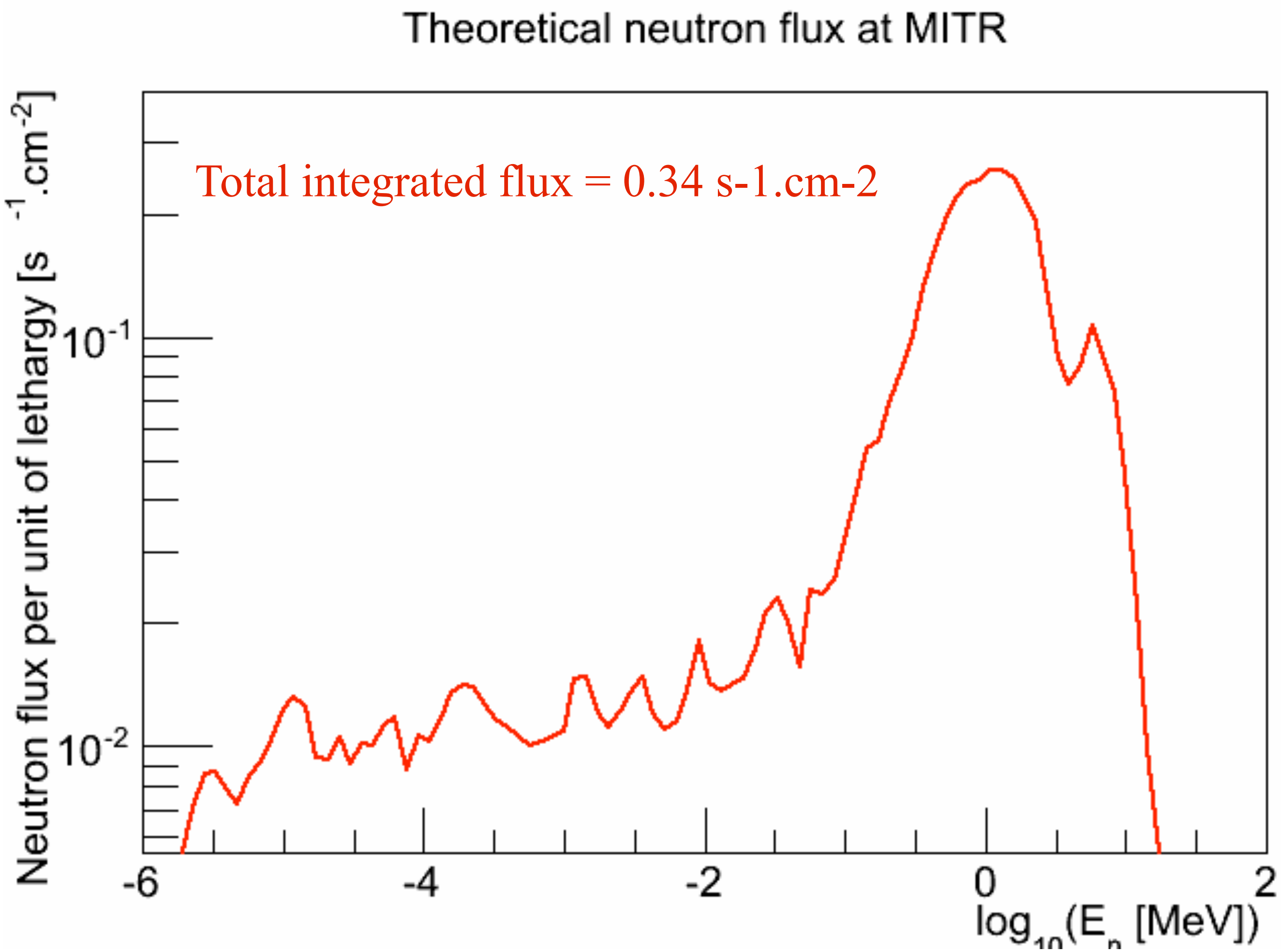
- A SuperCDMS Tower deployed at a reactor would see thousands of CEvNS events.
- The technology development, engineering design, readout, and operating procedures are all being done and paid for by the SuperCDMS SNOLAB Project.
- Background simulations and measurements need to be improved to understand the requirements of the shield around the detectors, including the need for active veto detectors.
- We are currently measuring the neutron background spectrum at MITR with two NCD detectors from SNO moderated by various layers of PVC.
- Ricochet could be deployed at a reactor in the next few years.

# Backup Slides

# Neutrons at MITR

- The room at MITR was designed for Boron Neutron Capture Therapy, a type of cancer therapy using epithermal neutrons.
- The room has a neutron beamline to deliver the neutrons from the reactor to the patient and moderate them into epithermal neutrons.
- When not in use, the beamline has a neutron “shutter” made of aluminum, PTFE, lead, water, and boronated concrete.
- A thesis with a detailed MCNP simulation of the reactor, the shutter, and the actual room exists.





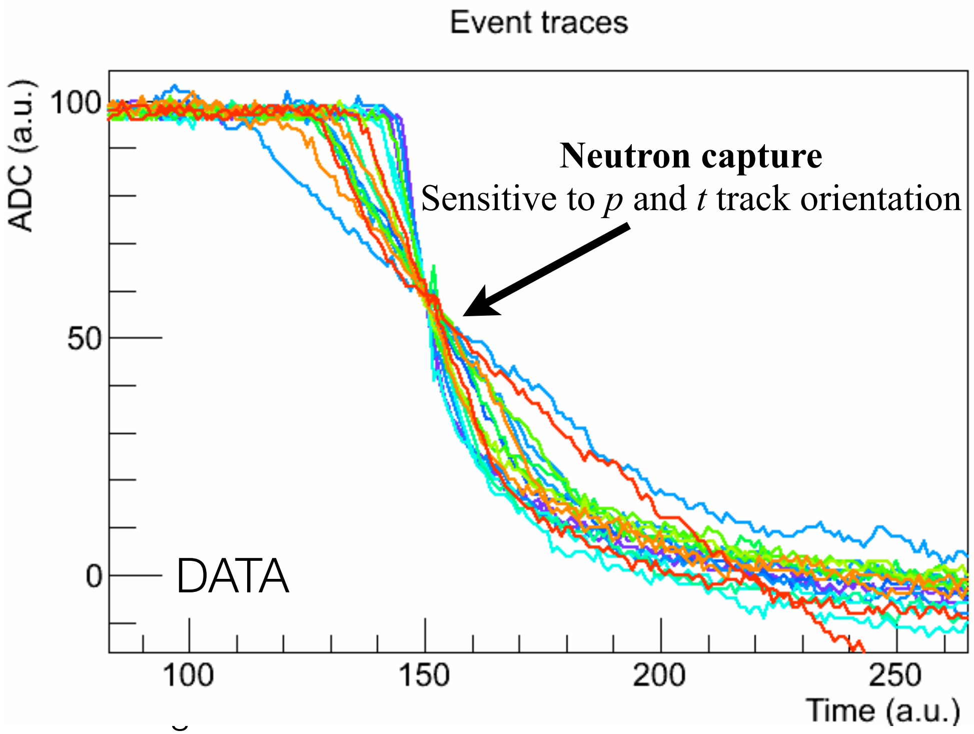

Need to measure neutron flux over 7 orders of magnitude with high precision

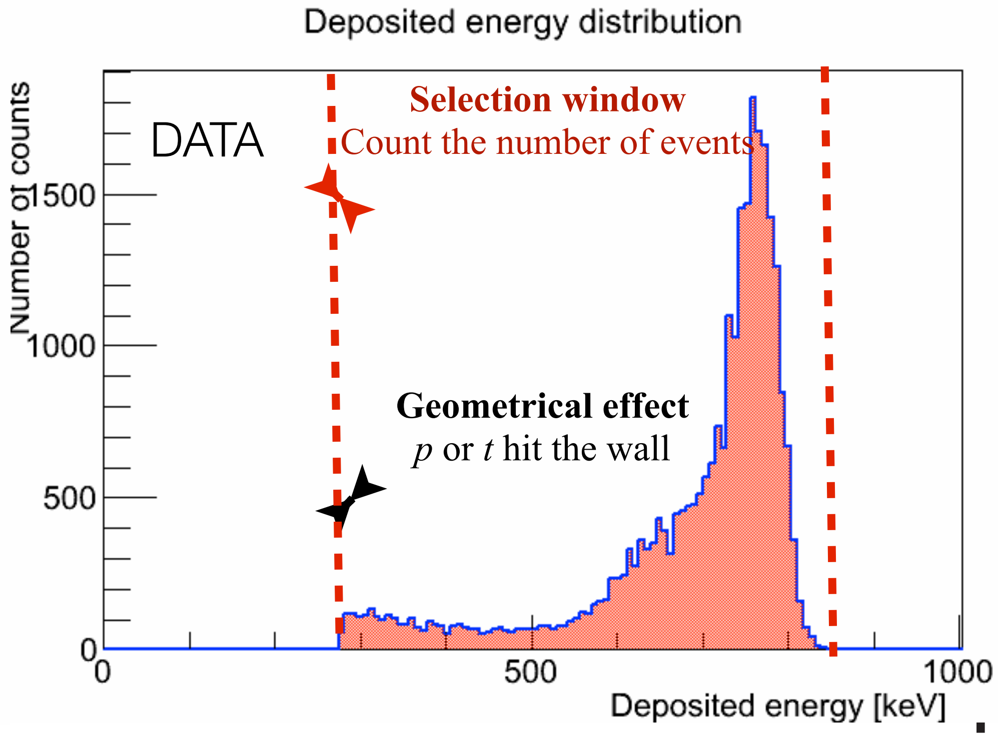
# Neutron monitoring

Use of He3 Neutron Capture Detector (NCD) based on the following process:

$$\mathrm{n} + {}^{3}\mathrm{He} \rightarrow \mathrm{p} + \mathrm{t} \quad (\mathrm{Q} = 764\ \mathrm{keV})$$

- **Cylinder shape:** 200 cm long, 5.08 cm diameter => active volume ~ 4000 cm3
- **Gaseous TPC:** 85% 3He + 15% CF4 @ 2.53 bar
- **Charge readout:** charge preamplifier Canberra 2001A
- **Optimal HV:** 1.95 kV
- **Energy resolution @ 764 keV**: 3.3%



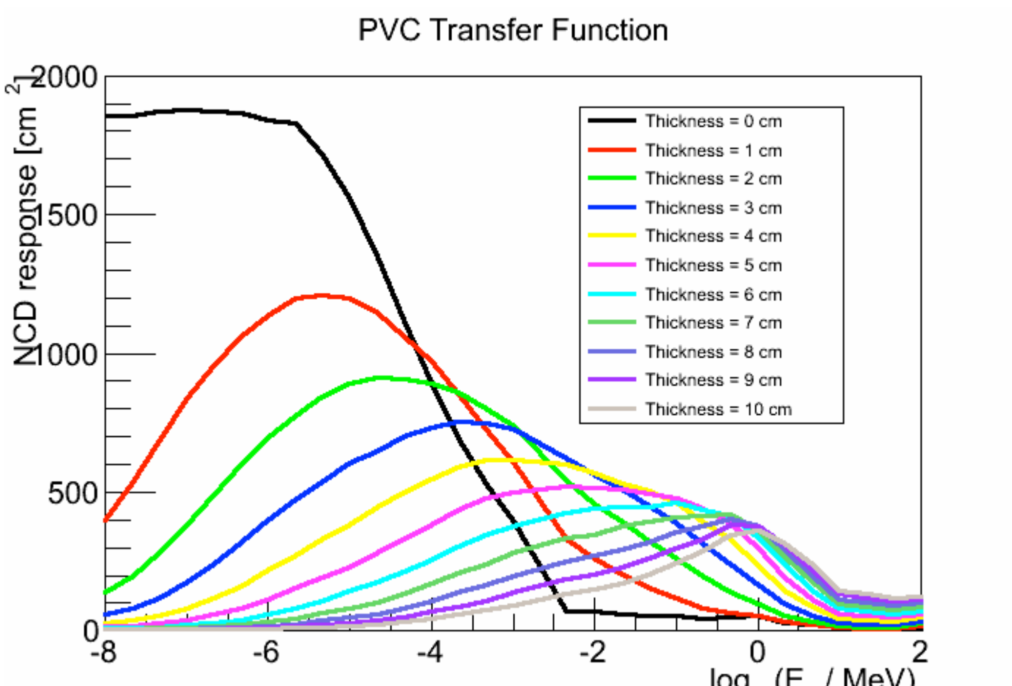
# Neutron monitoring

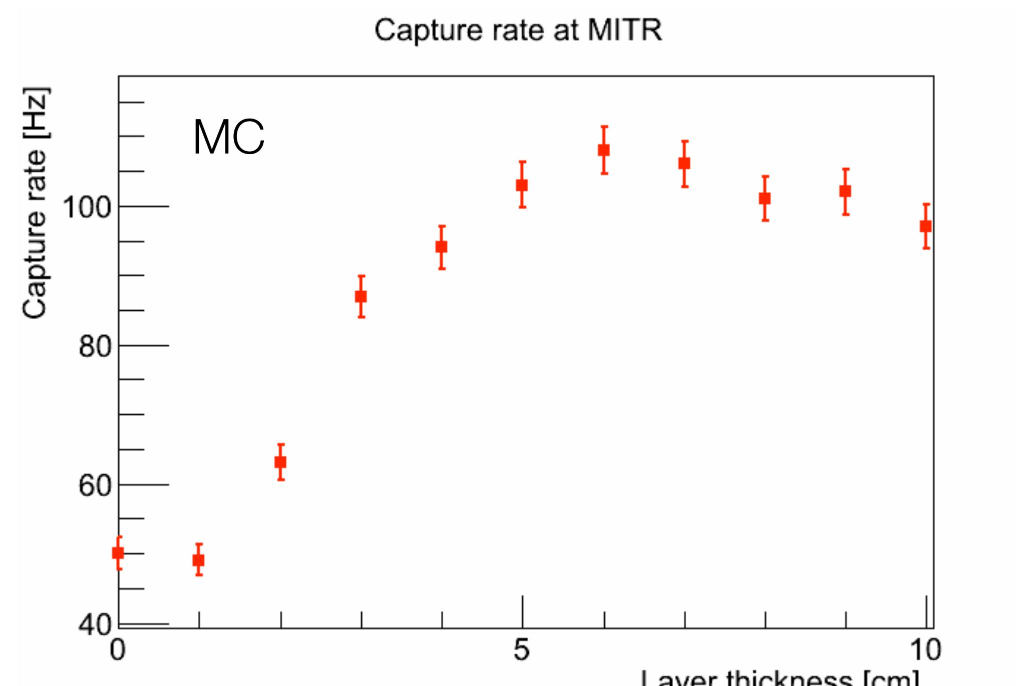
## A bonner sphere approach

NCD are mostly sensitive to thermal neutrons (cross section ~ 10^4 barns)

Use layers of PVC to slow down neutrons due to multiple collisions with hydrogen (mostly)

With PVC thicknesses up to 10 cm, we are sensitive to MeV neutrons!



# Neutron monitoring

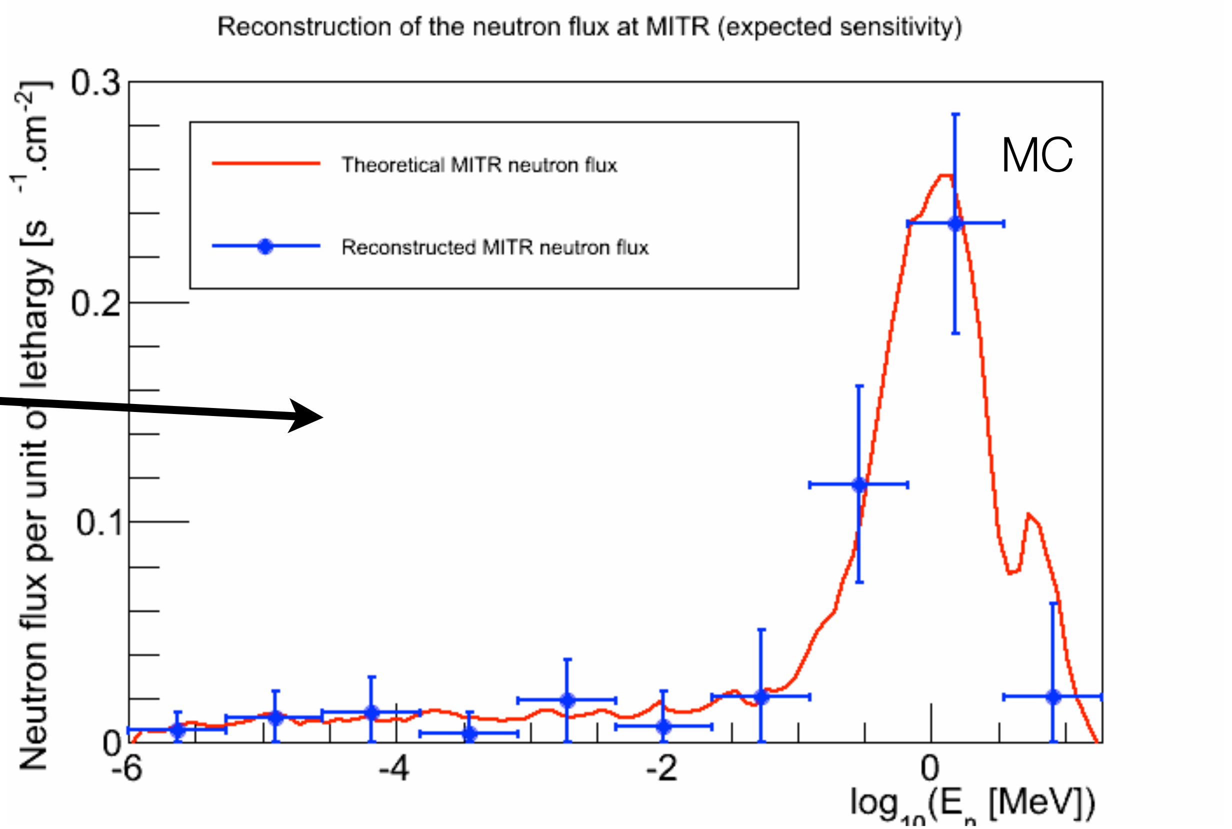
## Recovering the neutron flux from NCD rate measurements
## Likelihood approach

Definition of the likelihood function:

$$\mathscr{L}(\vec{F}) = \prod_{i=1}^{l} \exp\left[-\frac{(N_i^{th} - N_i^{obs})^2}{N_i^{obs}}\right]$$

Expected neutron flux reconstruction sensitivity using maximum likelihood distribution

This example considers:
- MITR theoretical neutron flux
- 10 neutron energy bins
- 11 PVC layers
- An acquisition time of **20 minutes** per layer




Reconstructed total flux = 0.348 ± 0.021 neutron /s/cm2 (~5% uncertainty)

Validation of the method using a monoenergetic deuteron neutron source is ongoing...

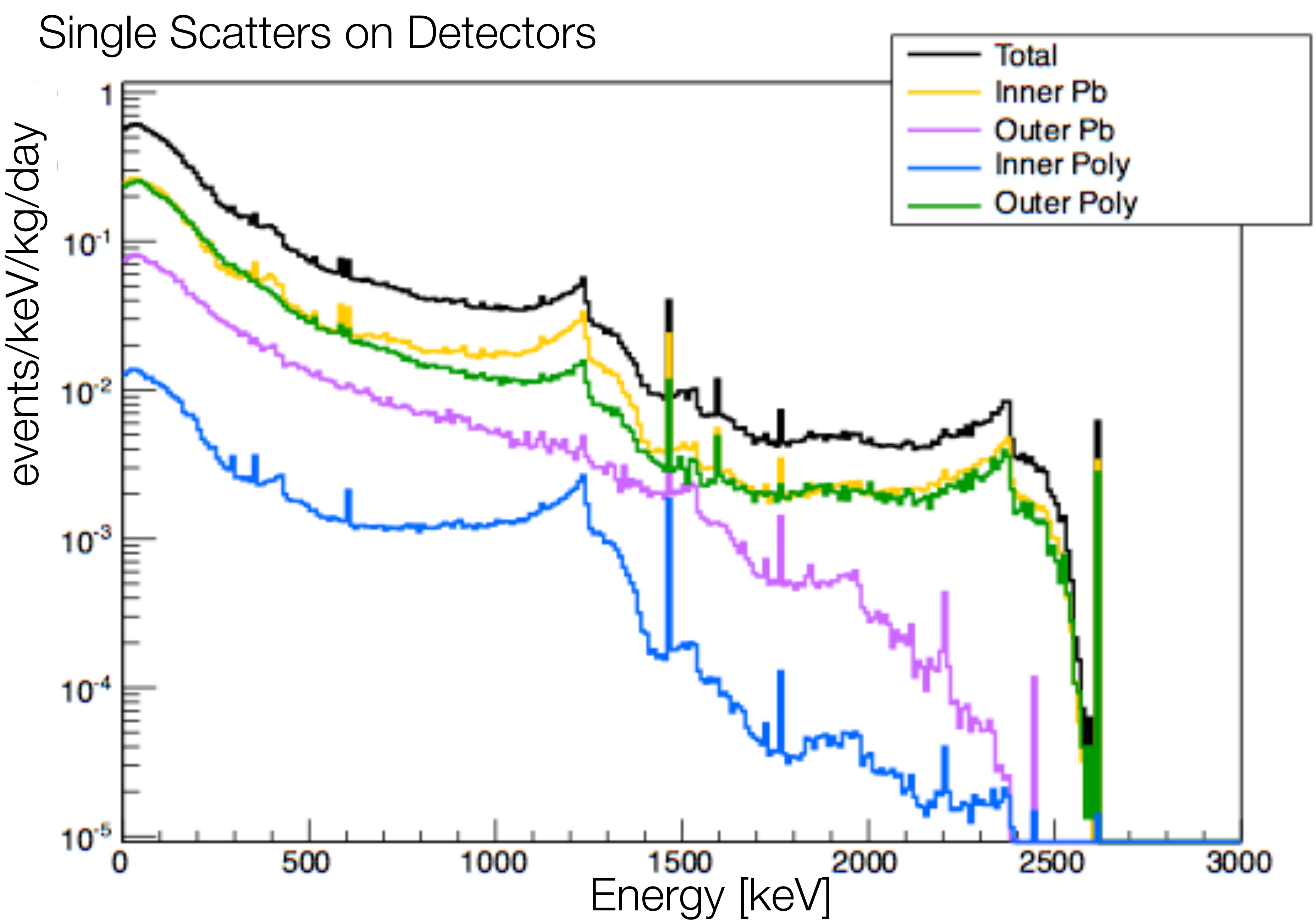
# Radiogenic Backgrounds

| Poly shield | Pb shield | Cu housing | Detectors |
|---|---|---|---|
| • U, Th, K | • U, Th, K | • U, Th, K<br>• Cosmic activation<br>• Radon Daughters | • U, Th, K<br>• Cosmic activation: L-, M-shell EC lines in Ge<br>•Radon Daughters |

# Contamination Assumptions

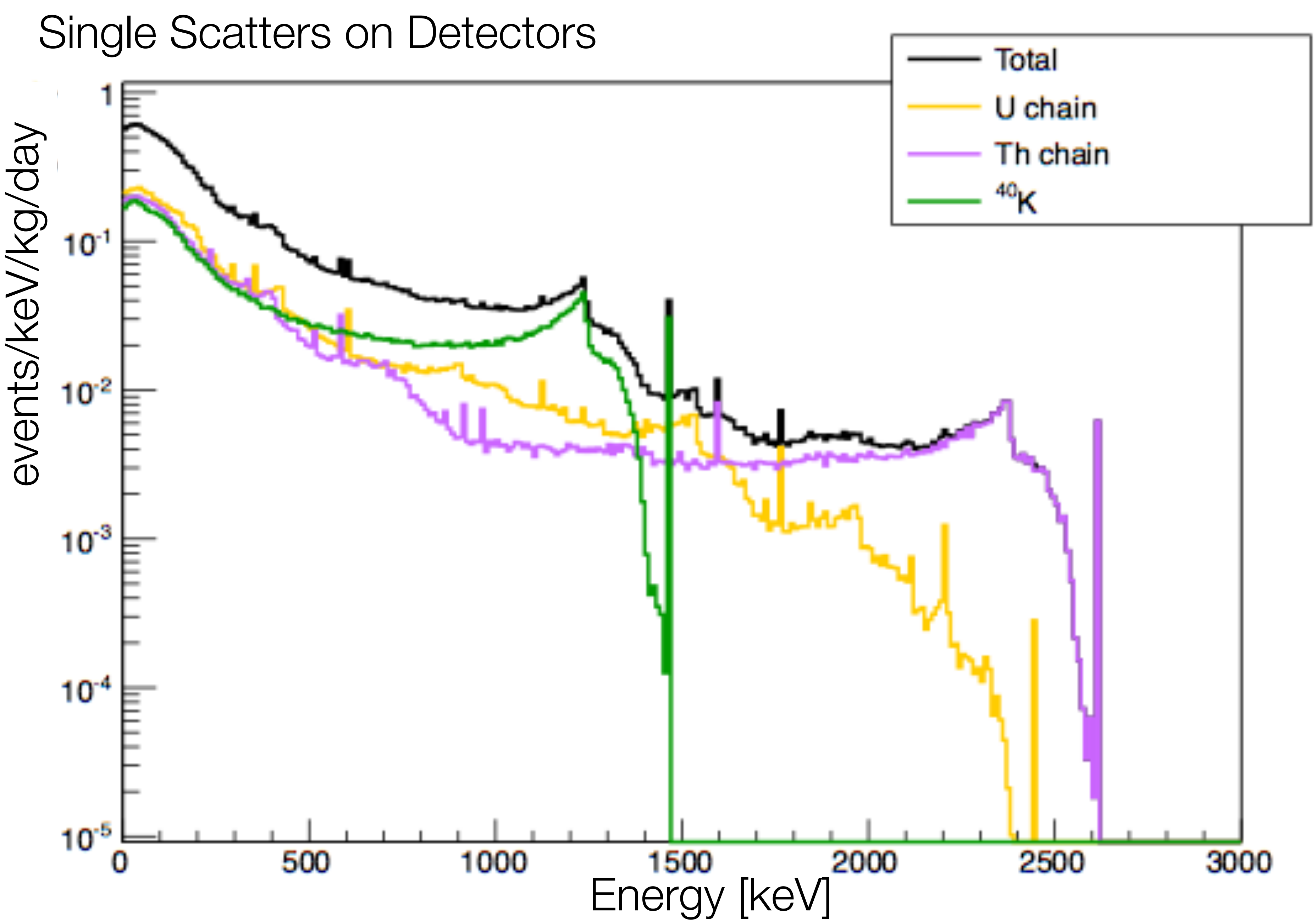
| | 238U [mBq / kg] | 232Th [mBq / kg] |
|---|---|---|
| Outer Pb | 3.8 | 9.4 |
| Inner Pb | 1 | 1 |
| Outer poly | 0.8 | 1.2 |
| Inner poly | 0.8 | 1.2 |

# U, Th Spectra



Single Scatters on Detectors
Total
Inner Pb
Outer Pb
Inner Poly
Outer Poly
events/keV/kg/day
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0
500
1000
1500
2000
2500
3000
Energy [keV]

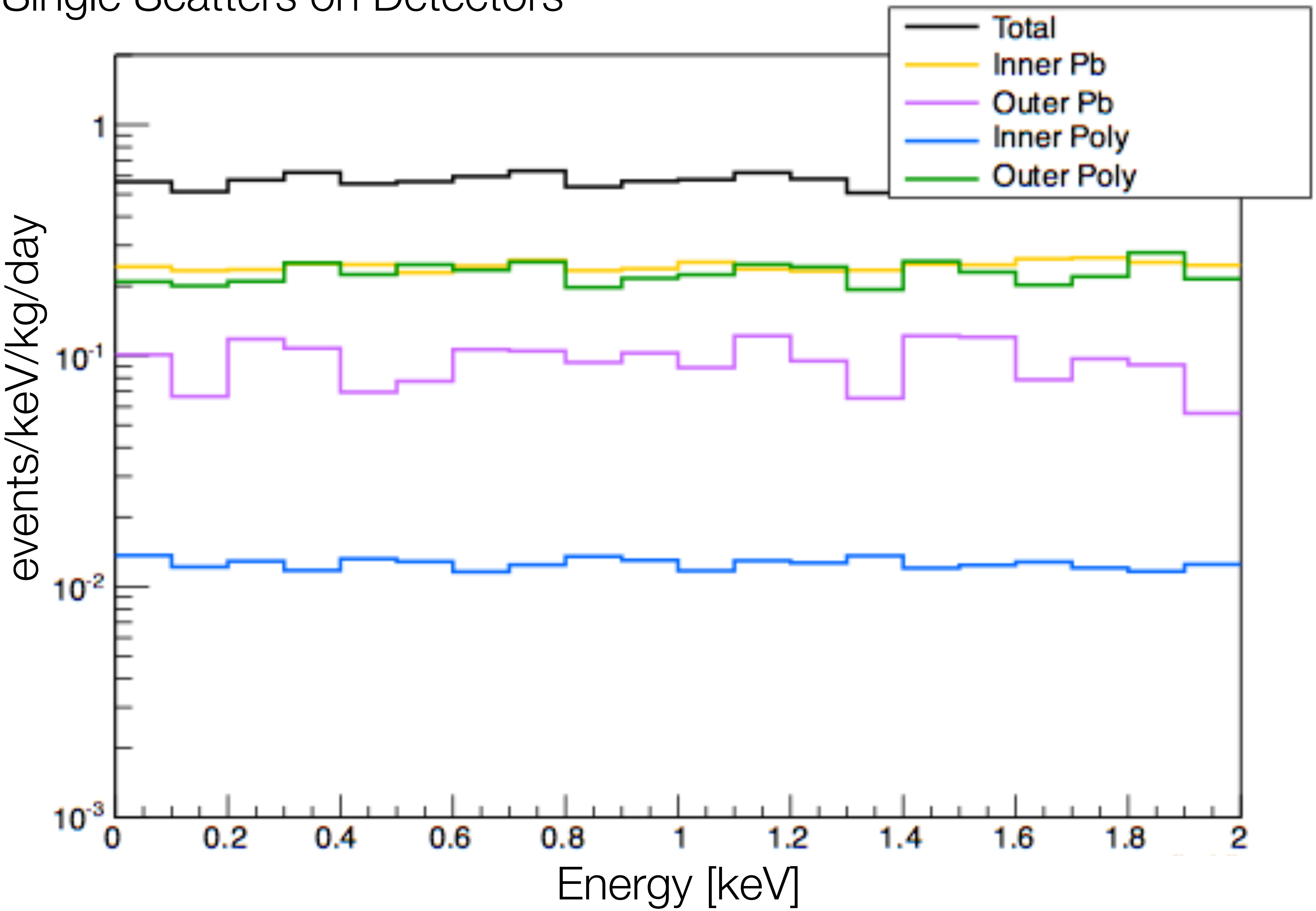
# U, Th Spectra



Single Scatters on Detectors
Total
U chain
Th chain
$^{40}$K
events/keV/kg/day
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
0
500
1000
1500
2000
2500
3000
Energy [keV]

# U, Th Spectra

Single Scatters on Detectors



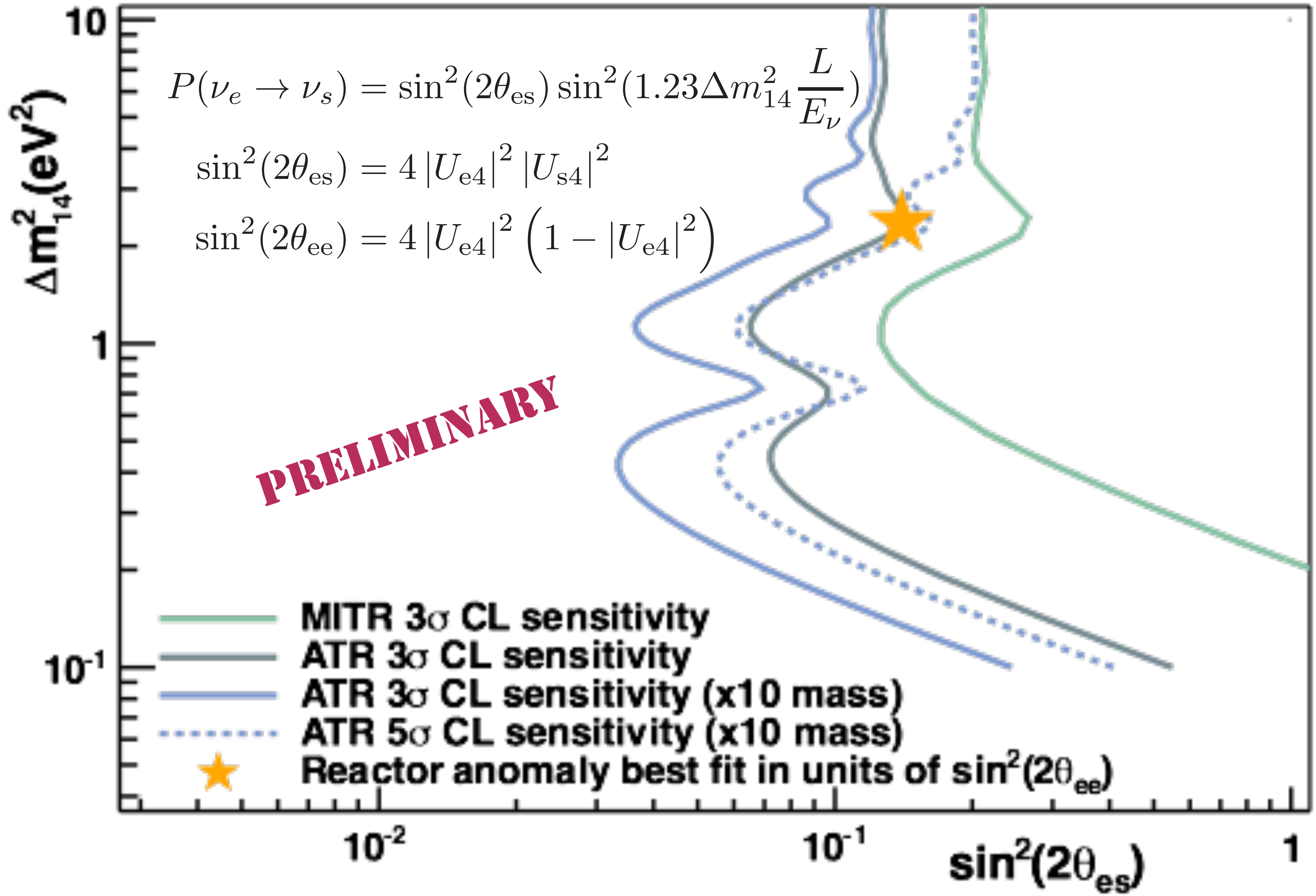
# Sterile Neutrino Search at the ATR?

If we mount the experiment on rails, can we search for sterile neutrinos at the ATR?
Oscillation length for 3 MeV neutrinos is around 3 m.

$$P_{\mathrm{osc}}(\nu_a \to \nu_b) = \sin^2(2\theta)\ \sin^2\left(\frac{1}{4\hbar c}\,\Delta m^2 \frac{L}{E}\right)$$

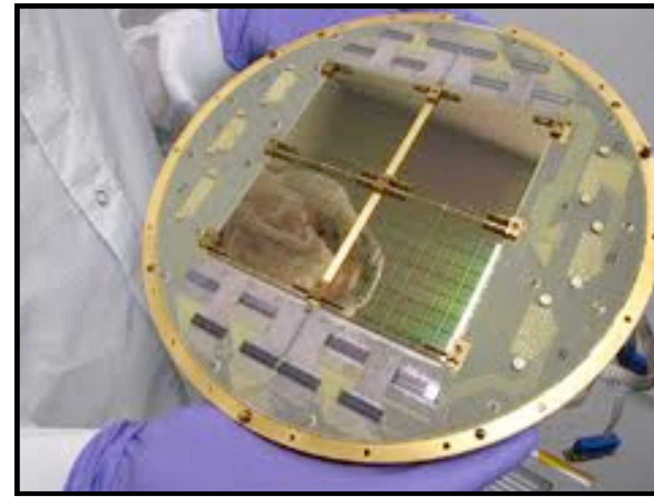
| | |
|---|---|
| Run period | 1 year at each baseline |
| Baselines | 4,6 m for MITR, 7,10 m for ATR |
| Target | Ge |
| Core size | 0.38x0.61 m for MITR, 1.2x1.2 m for ATR |
| Flux | $^{238}$U only, from Mueller |
| Neutrino rate | 3.2E25 $\overline{\nu}$/year for MITR, 6.4E26 $\overline{\nu}$/year for ATR |
| Active volume | 10 kg |
| Detection efficiency | 60% |
| Background (flat spectrum) | 4.4 cts/kg/day in 6 kg fiducial |
| Energy threshold | 100 eVr |
| Flat syst. unc. (mostly flux norm.) | 2% |
| Correlation coefficient between baselines | 0.99 |
| Energy smear near threshold | 20% |

# Sterile Neutrino Search



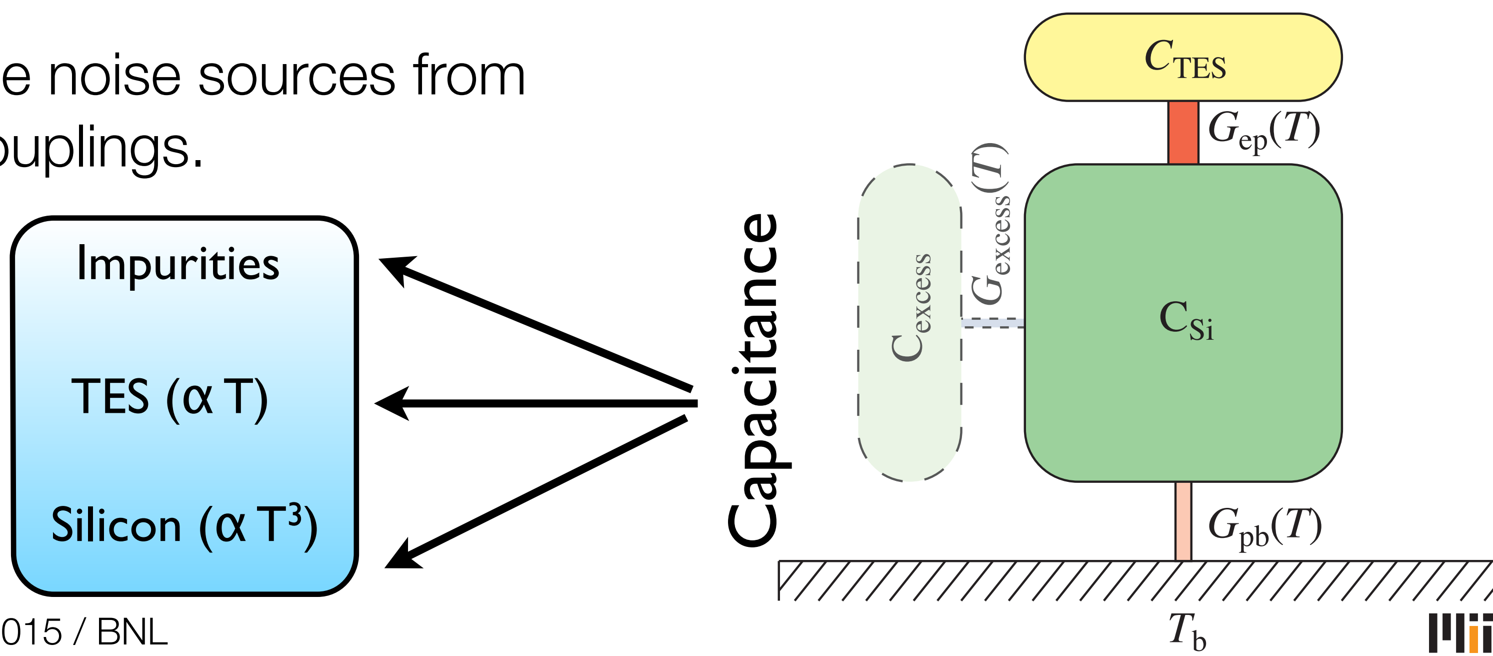
# Ricochet Phase 2
# (MeV-scale Neutrinos)

# The Detector



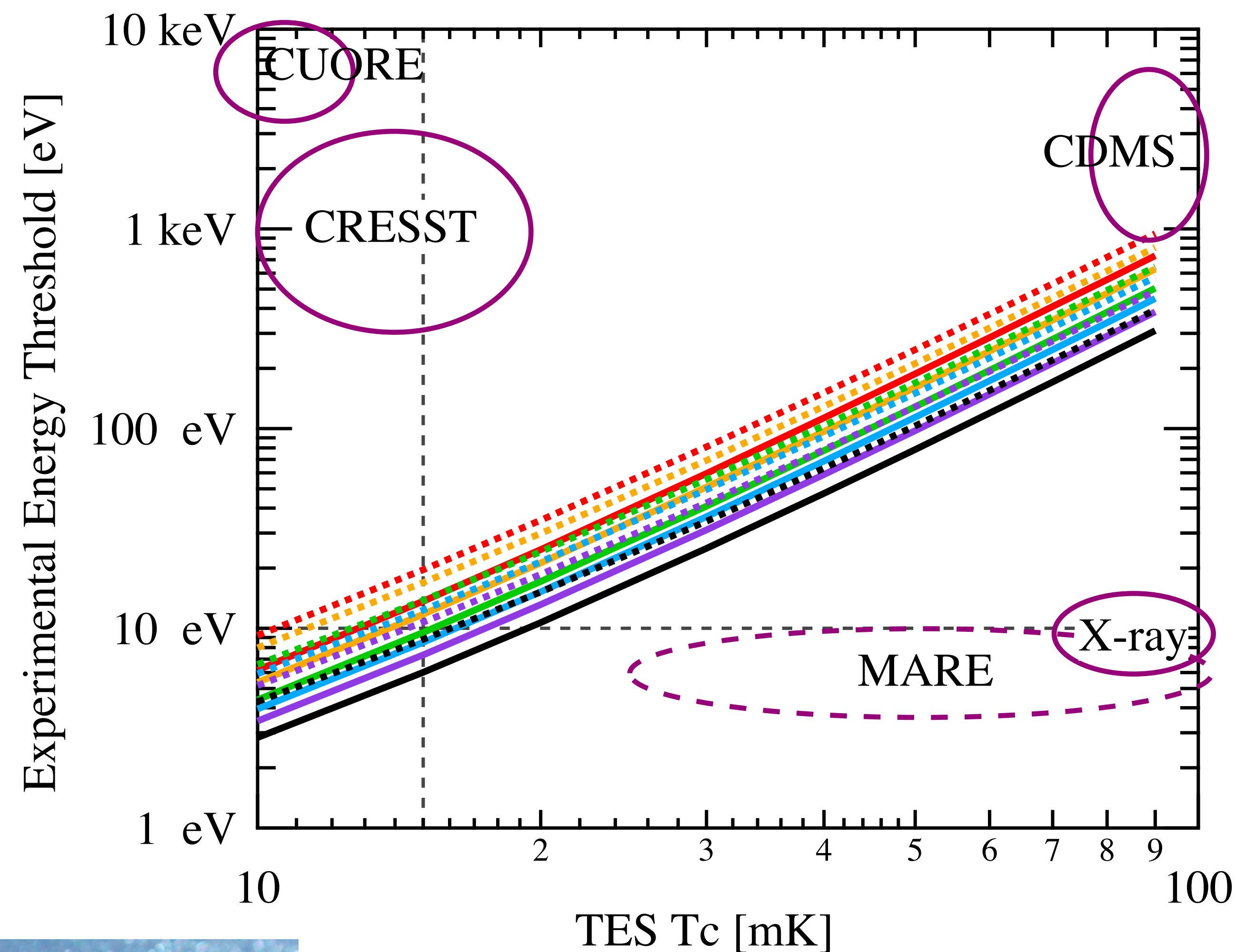
- Given historical precedent, we focus on Transition Edge Sensors (TES) as the technology to push down to the 10 eV scale.
- Energy resolution dominated by the total heat capacitance of system (Ctot).
- At 15 mK, a 10 eV threshold could be achieved with a system capacitance of Ctot < 300 pJ/K.
- Model must include noise sources from other internal decouplings.

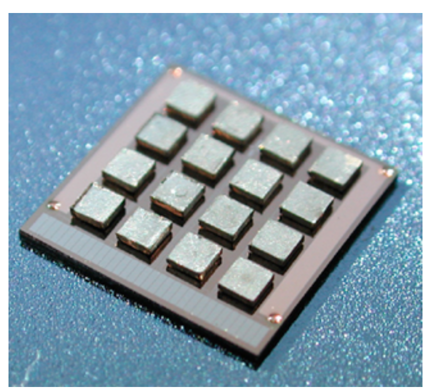
$$\sigma_E \approx \sqrt{\frac{4k_B T^2 C_{\text{tot}}}{\alpha}\sqrt{\frac{\beta+1}{2}}}$$

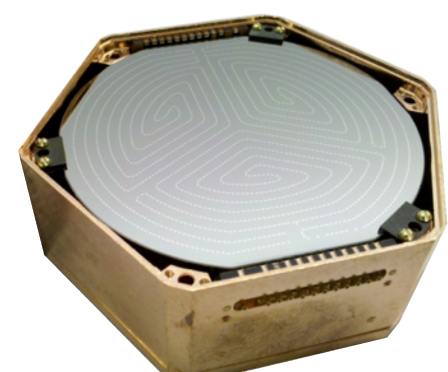


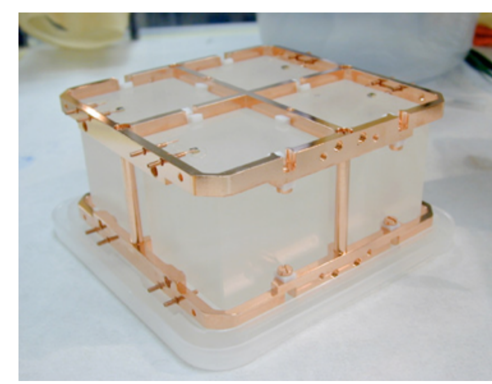
# Detector Optimization

- System's mass optimized to reach 10 eV threshold assuming 15 mK temperature.
- Yields 50 g Si (20 g Ge) cube.
- Signal pulses show remarkable linearity.







# Backgrounds and Systematics

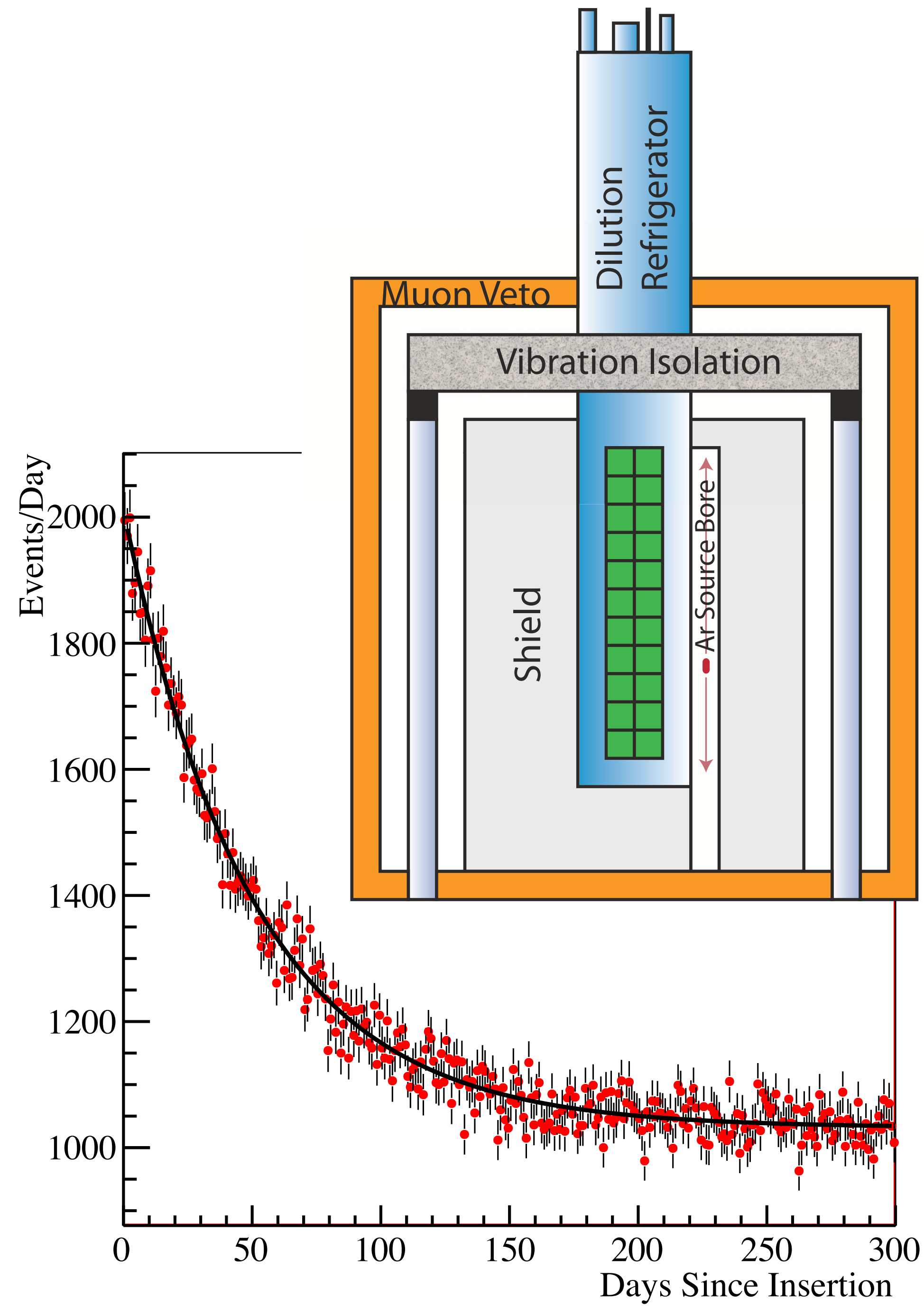
- Backgrounds stem from various sources:
- Radiogenic impurities (U, Th, 60Co, and 3H). Most have signatures well above region of interest. Some, like 3H, have betas that have phase space in ROI.
- Compton and photo-absorption.
- Surface photons from atomic transitions.
- Neutrons (< 0.1 eV/kg/yr in 10-100 keV, from CDMS measurements)
- Neutrino-elastic scattering (not in energy range)

| Source | Systematic | |
|---|---|---|
| | Global | Shape Only |
| Source Strength | $\pm 1\%$ | - |
| Cross-section | $\pm 1\%$ | - |
| Detector Variation | $\pm 2\%$ | $\pm 2\%$ |
| Absolute Efficiency | $\pm 5\%$ | - |
| Source-Induced Background | $< 1\%$ | $< 1\%$ |
| Vertex Resolution | $\pm 2.8$ cm | $\pm 2.8$ cm |
| Source Extent | $\pm 4$ cm | $\pm 4$ cm |
| Total Systematic | $\pm 5.5\%$ | $\pm 2\%$ |
| Statistical (Whole Array) | $\pm 1\%$ | |

Estimates from CDMS place background at 40 events/kg/day/keV in the 1-10 keV region. Leads to 1-2 events/kg/day in ROI

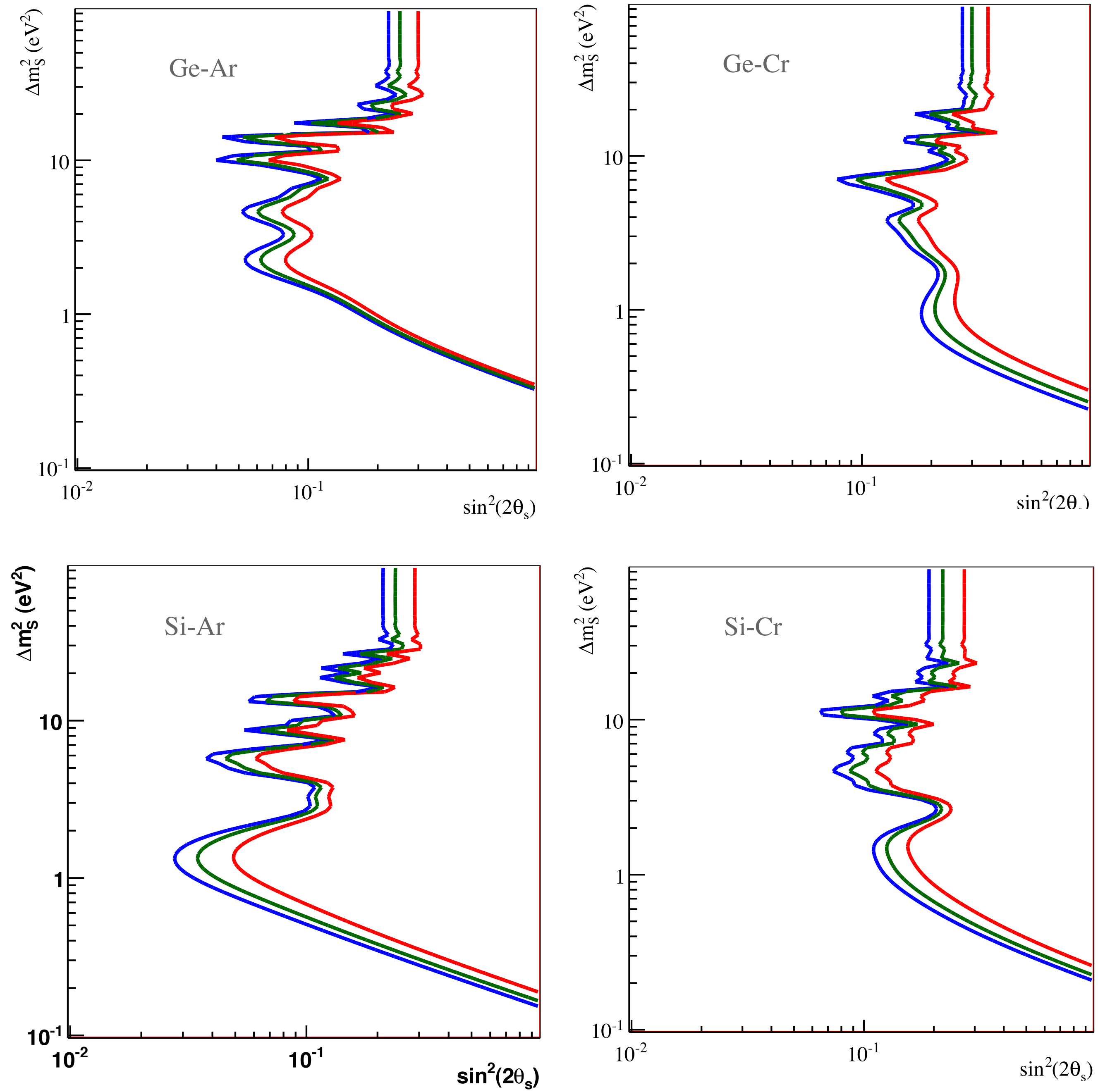
# Sensitivity Studies

- Wanted to determine what the potential sensitivity of such an experiment for a sterile neutrino at the 1 eV mass splitting scale.
- Array of 10,000 elements with Ar/Cr source just outside shield (10 cm closest distance).
- Measuring time of 300 days (for Ar, equivalent of 50 days signal, 250 days background).
- Background rate of 1 event/kg/day



# Results

- Sensitivity study performed on 10,000 element array (500 kg Si, 200 kg Ge),  Ar or Cr source
- Assumed 300 day measuring time with background rate of 1 event/kg/day.
- Analysis on shape + rate (bulk result from shape)
- Mock signal also tested.



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**<u>Alternate Measurements</u>**

CEvNS measurement

$\sin^2\theta_W$ measurement

dark matter detection